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GEOHAZARDS theme REPORT

2003

IGOS an Integrated Global Observing Strategy
for the monitoring of our Environment from Earth and Space

The societal impact of geological and geophysical hazards is enormous. Every year volcanoes, earthquakes, landslides and subsidence claim thousands of lives, injure many thousands more, devastate peoples' homes and destroy their livelihoods. The costs of damaged infrastructure are taken higher still by insurance premiums and run into the billions in any currency. This affects rich and poor alike, but with a disproportionate impact on the developing world. As the human population increases and more people live in hazardous areas, this impact grows unsustainably. It must be reduced and that requires increased understanding of the geohazards, improved preparedness for disasters and better ways to manage them when they occur.

The inter-related disasters that comprise geohazards are all driven directly by geological processes and share ground deformation as a common thread. This means that they can be addressed using similar technology and understood using related scientific modelling processes. Geohazards are a complex phenomenon and no one method can provide all the necessary information and understanding. It is essential that spaceborne Earth Observation data are **integrated** with airborne data, in-situ observations and associated historical data archives, and then analysed using Geographic Information Systems (GIS) and other modelling tools if these hazards are to be understood and managed. Geohazards occur in one form or another in every country. They do not respect national boundaries and have the potential to cause changes in the atmosphere that will be truly **global** in effect, requiring a global **observing** infrastructure to monitor them. There are also human issues in organising the Earth Science community to meet these challenges that demand an appropriate **strategy** if they are to be addressed successfully. This document sets out such an approach, in the framework of the Integrated Global Observing Strategy (IGOS). IGOS is an initiative pursued by a partnership of international agencies that make and use global observations. Its aim is to coordinate and integrate satellite and in-situ observations, thereby advancing understanding of the way the various Earth systems work and enhancing society's ability to manage their impacts.

The goal of the geohazards IGOS is to integrate disparate, multidisciplinary, applied research into global, operational systems by filling gaps in organisation, observation and knowledge over the next decade. The pursuit of this goal will improve the provision of timely, reliable and cost-effective information to those responsible for managing these hazards and increase the capacity of all nations to be resilient in the face of the related disasters. The strategy addresses the mapping, monitoring, forecasting and related preparedness activities needed to underpin crisis response, via the provision of critical information products to be used by the agencies involved in disaster management initiatives. Addressing this goal will fill key gaps in the provision of long-term observations and in a number of integration issues that are not covered by the disaster response systems set up under the International Charter on Space and Major Disasters or the United Nations (UN) Action Team on Disaster Management. The strategy identifies four main strategic objectives: to build the capacity of the global geohazards community; fill gaps in observations related to topography, deformation, seismicity and mapping; increase integrated applications of data from multiple sources and by multidisciplinary approaches; and promote the take-up of the defined best practice developed in specific studies on a global basis.

An action plan is proposed to address these objectives in the short, medium and long term over the next ten years. Capacity building will be undertaken by strengthening the Geological Applications of Remote Sensing (GARS) Programme with space agency participation, to create a coordinating mechanism for implementing the Geohazards IGOS. A review will be conducted to identify accelerated exploitation routes for existing observations, for example by securing the release of existing global topographic datasets. It is important that continuity is achieved and maintained for the four key observations identified above. Continuity within existing C-band missions has demonstrated the utility of SAR interferometry for measuring deformation over bare surfaces. In the long term, a programme must be established to deliver continuity of L-band SAR interferometry, so that this can be extended to vegetated surfaces. On the ground, attention should be paid to the provision of increased coverage and density of seismic networks. Integration will be taken forward by projects designed to release the synergy from coupling such synoptic and periodic observations from space with detailed, continuous point observations on the ground, like those offered by networks of Global Positioning System (GPS) receivers. These projects require a range of disciplines to work together using modelling and visualisation tools, providing other kinds of integration. The results will be disseminated using workshops, publications and the Internet in order to spread best practice. Geohazards databases containing "strategic datasets" will be promoted and mechanisms for sharing data, information and knowledge on an operational basis streamlined. Curricula will be designed to generate new training courses, extending capacity building to the developing world and promoting knowledge and technology transfer.

The main players responsible for implementation are committed to act. This strategy explains how they intend to do so and is aimed primarily at the international geohazards user community, especially scientists working in monitoring and advisory agencies who turn the observations into information products. The strategy also pays close attention to the end users in responsible authorities managing geohazards on a daily basis, research scientists developing the underpinning knowledge base and the IGOS partners making the observations. It is based on society's need to reduce the impact of geohazards on lives, property and economies over the long term. Assessment will be made against individual objectives during the lifetime of the strategy but ultimately it must be judged against the following criteria; has it saved lives, reduced damage to infrastructure and saved money, thereby limiting the impact of geohazards on society as a whole? ■

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Chapter 3 lists the main observations required in order to address the users' needs for each of three geohazards, emphasises four common and three specific observational requirements and then goes on to describe the most important existing and planned in-situ, airborne and satellite-based observation systems needed to make them

Chapter 4 describes a series of issue relating to integration including data management, modelling and assimilation, human and technological networks, and building capacity in the geohazards community via knowledge and technology transfer, education and training

Chapter 5 is the heart of the strategy. It examines the gaps in observations, key systems, integration and scientific knowledge that must be filled if the geohazards IGOS is to succeed. Recommendations are made for areas to be addressed in order to fill the key gaps over the next decade

Chapter 6 shows how the strategy will be implemented, setting out specific short, medium and long-term actions, demonstrating how the key players are committed to act, and proposing a mechanism for leading the IGOS Geohazards Theme, monitoring its implementation and providing feedback on progress toward the strategic objectives

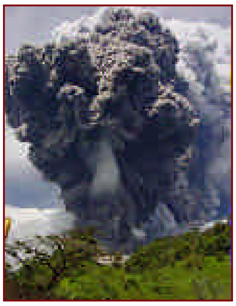
Every year thousands of people are killed by volcanic eruptions, earthquakes and landslides. With the related phenomenon of subsidence, they are one of the main natural causes of damage to human settlements and infrastructures. They severely disrupt the economic life of many societies across the globe. As the human population increases and habitation on hazardous land areas becomes more common, the risks posed by these hazards increases. The need to observe their behaviour, understand them better and mitigate their effects becomes ever more urgent and is the driver behind this strategy.

GEOHAZARDS' IMPACTS

Geohazards such as earthquakes, volcanic eruptions, landslides and subsidence inflict an enormous cost on society. Every year thousands of people are killed by volcanoes, earthquakes and landslides; the United Nations Environment Programme (UNEP) on its Geo Data portal reports that more than 26,000 have died in volcanic disasters between 1975-2000 and the death toll of the 1976 earthquake in Tangshan, China alone was 242,000. Yet this is only part of the toll; for every life lost, many more are injured, or lose their homes or livelihoods; landslides in Bolivia in 1994 affected 165,000 people. A major disaster disrupts the economic life of a society for years or even decades. Even where loss of life is avoided, geohazards damage infrastructure, destroying roads, railways, buildings, airports, pipelines, dams, power grids and many other structures.

The cost of these events is billions in any currency and they affect the richest and poorest countries alike. The United States Geological Survey (USGS) report that immediate damage from the Mount St. Helens eruption in 1980 was US$1 Billion. Consequently, private organisations most exposed to these risks seek to insure against them at an additional cost that is itself in the billions. The United Nations (UN) has established that the total costs of natural disasters as a whole have risen unsustainably, 10 fold in the past 40 years. The principal driver is the increase in human population and a consequent increase in the intensity of development in hazardous areas such as stepper slopes and the coastal zone. The increasing risks posed by geohazards to all societies require better understanding of the hazards in order to provide a better means to deal with them.

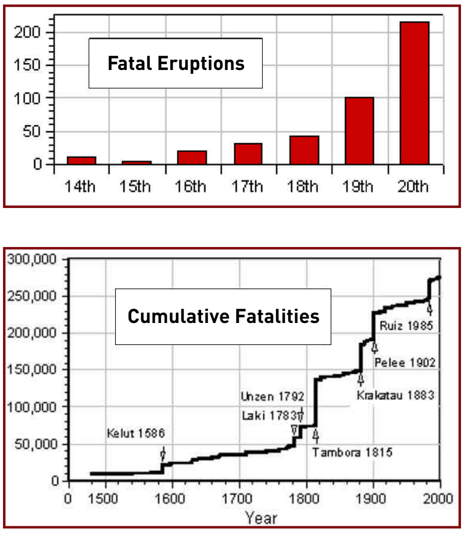
Volcanoes and volcanic eruptions have captured the imagination of the human race for many centuries. In earlier times, eruptions caught the local population by surprise and often caused great loss of life, in addition to inflicting material damage on nearby areas that lasted for decades or centuries. Even today, with the flood of other news served up daily, there is a ready audience for reports of any volcanic activity. This shift from regarding volcanic eruptions as completely unpredictable and terrible events, to viewing them as one of nature's foremost made-for-television spectaculars, reflects in part the increasing success of volcano scientists in interpreting signs of volcanic unrest and communicating the risk to local authorities and the general



Left: Pyroclastic eruption of Reventador Volcano, Ecuador, November 2002. (photo from website of the Instituto Geofisico, Quito, Ecuador). Right: Piton de la Fournaise - La R union - Eruption November 2000 (copyright T. Staudacher/OVPF/IPGP)

public. This complacency is dangerous, however. For all our relative successes in understanding volcanoes, many very important aspects of volcanic activity remain poorly understood. Many active volcanoes in inhabited areas are inadequately monitored. Furthermore, because of the increase in population worldwide, the number of people and the total cost of social infrastructure close to active volcanoes are increasing. Recent examples include: El Chichon, which was completely unmonitored prior to 1982, when it erupted, killing 1800 people and devastating the surrounding area for a decade; and Nyiragongo, where over 70 people were killed by fast-moving lava flows in 1977, was known to be poorly monitored, and was identified as a Decade Volcano under the UN-sponsored International Decade for Natural Disaster Reduction (IDNRD). Nevertheless 25 years later, the January 2002 eruption of Nyiragongo killed 147, and wiped out the centre of Goma, a town of over half a million people. Evidence for increased exposure to volcanic hazards includes a steady increase in the number of fatal eruptions over the last 500 years (Simkin and others, 2001).

The USGS reports that every year some 12,000 to 14,000 earthquakes (approximately 35 per day) are recorded by the seismic networks all around the



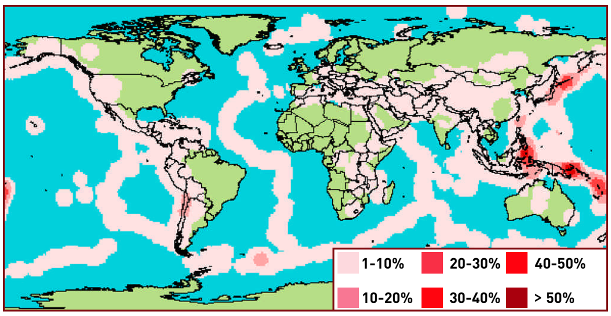
Fatal eruptions (14th century to present) and cumulative eruption fatalities (1500 to present). The overall exposure of human population to volcanic activity can be seen in the first graph, where the number of eruptions causing at least one death has steadily increased, over the last 5-6 centuries. The second graph shows that most of the lives lost during this period were lost in a few, very large eruptions. (from Simkin, Siebert and Blong, 2001)

world: at least one of these will have a Magnitude 8 or higher and 120 are of Magnitude 7-7.9. According to the UNEP, between 1975 and 2000, more than 460.000 people were killed by earthquakes worldwide and more than 8 million people became homeless as consequence of an earthquake.

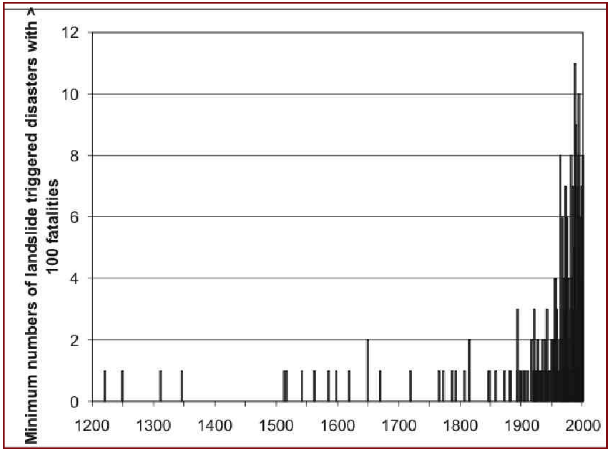
Plate tectonics provides a framework for understanding earthquake activity, the earthquake-prone regions of Earth are well delineated and global seismicity information is available in the form of maps or catalogues. However, there is a need to enhance identification and characterisation of particular seismogenic structures and individual zones of deformation contributing to the known regional seismic zones. This requires enhanced observation and monitoring of deformation plus making the best use of existing information such as background seismicity and geological settings. It will be the first step towards the creation of more accurate hazard maps in order to increase preparedness and support mitigation efforts. The ultimate aim is to identify and define earthquake precursors that will allow prediction. Successful short-term predictions have been made for few earthquakes, but most predictions have been unsuccessful and this remains an area for basic research.

Ground Instabilities are among the most widespread geological hazards on Earth. They range from devastating landslides involving the chaotic movement of large quantities of rock and soil down steep, unstable slopes to the gradual but insidious collapse of large coherent areas of the ground surface due to changes in subsurface stability. The common feature of them is ground failure observable through surface displacements and deformations. As with the other geohazards, they cause thousands of deaths and injuries and enormous economic loss around the world. Their destructive effects are greatest in developing countries, where there are an average of a thousand deaths per year, but even in developed countries deaths are in the hundreds. Non-fatal impacts are economic, with a recent study commissioned by the British National Space Centre (BNSC) and conducted by the British Geological Survey (BGS) and Nigel Press Associates (NPA) estimating that the cost of subsidence in the United Kingdom amounts to 500M Euros every year. They form an increasing threat taking into consideration world population growth, consequent intensive land use on steep slopes and in the coastal zone and the potential increase in triggering events like major storms due to climatic change. Although individual landslides occur at single locations, the phenomenon can affect large areas and thereby have an affect as widespread as an earthquake. For example, the Bola cyclone in March 1988 triggered more than nineteen thousand landslides covering an area of fifty square kilometres in New Zealand (Glade, 1997).

Prediction, mitigation and management of ground instabilities is therefore of socio-economic importance for the whole community. Achieving this will require much better maps showing which areas are exposed to these hazards; the widespread occurrence means that



Annual probability of earthquake occurrence within 200 km with a Magnitude greater than 5,4 on Richter scale.
Data source: Council of the National Seismic System (CNSS). Data analysis, mapping and printing: UNEP/GRID-Geneva, June 2000. (from http://www.grid.unep.ch/)



Minimum frequency of natural disasters caused by landslides of more than 100 casualties. This figure is indeed heavily dependent on available reports, however, it offers some information on increased casualties due to landsliding. The implication is twofold. Landslide occurrence might have increased, or, as a result of population growth, more people has moved into more disaster-prone areas. It can be suspected that both factors are responsible for the shown trend. (from Glade & Dikau 2001)

basic inventories are lacking in many regions. In addition, there are several aspects of ground instabilities that need to be better understood, because of the complexity of causative factors, the variety of triggering mechanisms and the different temporal and spatial scales involved.

RESPONSES

Events such as the 1999 Kocaeli earthquake in Turkey, the 2002 eruption of Nyiragongo Volcano, which cut the city of Goma in two, and the recent series of devastating landslides in South America and Italy have caught the attention of the world. The costs of geohazards are clear and therefore these issues are increasingly prominent on the political and social agendas of many governments and international agencies. At a global scale, the benefits of mitigation have been explored at length during the 2002 World Summit on Sustainable Development (WSSD). Benefits demonstrated by several case studies are described in Chapters 2 and 3 and include a reduction not only in the lives lost but also in the damage to infrastructure. In the longer-term, the money no longer spent on disaster response could be transferred to more proactive development initiatives. The summit therefore decided to strengthen capacities and to promote systematic, joint international observation and research, recognising the role an integrated global observing strategy can play in this process. It recommended an integrated, multi-hazard approach to prevention, mitigation and preparedness.

On a national and regional level, the European Commission (EC) and the European Space Agency (ESA) are jointly driving a political agenda on this theme that includes development of Global Monitoring for Environment and Security (GMES), facilitating and fostering the timely provision of quality data, information and knowledge and increasing the operational use of satellite observations. Both these organisations are funding relevant work within their regular Programmes such as the EC's Sixth Framework and ESA's GMES Service Element (GSE) and Data Users Element (DUE). In North America, the National Aeronautics and Space Agency (NASA) has published "Living on a Restless Planet" to encourage work in this area. The Earthscope initiative is receiving significant funding from the US National Science Foundation and other agencies to study geohazards on a continental scale. There are similar initiatives in other regions and international funding agencies increasingly fund work on the topic, as do national funding agencies such as the UK's Department for International Development. But there are several things missing that make all this work harder to undertake and less productive.

THE NEED FOR A STRATEGY

Several factors determine the need for a strategic approach to this issue. Firstly, there is a lack of an **integrated** approach. The scale of the problem demands the cooperation from all affected societies and within all relevant technical fields. Existing initiatives on specific topics need bringing together under one umbrella. The user and scientific communities need to come together so that those who deal with the problems in the real world interact with those who have potential solutions. Technologies and methodologies that each address part of the problem will have more effect if used in concert as part of a multidisciplinary approach. For example, ground-based measurements can be continuous in time but are often limited in extent, whereas satellite observations are periodic but cover wide areas in a uniform fashion. A model developed to understand a well-monitored volcano might help explain the behaviour of another despite a lack of adequate measurements. The geohazards lend themselves to such an approach. Such integration will have the benefit of releasing the synergy that is found in using complementary methods and the accelerated learning that comes from a multidisciplinary approach.

Secondly, geohazards arise from **global** geological processes inside the Earth driving movement and deformation of its crust. Ground deformation is the linking phenomenon and so similar modelling and observational techniques can be used to address all these hazards. They are also global in extent, occurring on all the continents, affecting the citizens of every country, and causing problems for every government. They do not respect national boundaries and so cannot be dealt with at the national or regional level. An earthquake may span several countries or send refugees from one into another. A catastrophic volcanic eruption could put enough gases and particulates into the atmosphere to affect global climate severely, as demonstrated by the Pinatubo eruption of 1991. Responses need coordination on a global scale that matches the scale of the problem itself.

Thirdly, current **observations** are inadequate and the lack of historic databases constrains our approach. For example, few countries in even the developed world have inventories of historic landslides, yet these are the first step in understanding where landslides will occur in the future. By no means are all faults mapped and the interseismic processes along those that are mapped are poorly understood. A few volcanoes are well monitored but many are not yet observed in any detail. A range of observations is commonly needed: topography and landform, deformation, strain, geology, soil, land-use, temperature, rainfall, moisture and gases, to name a few of the more important. Some can be observed from space, taking advantage of Earth Observation (EO) systems already in orbit. These can offer significant cost-savings compared to other means of gathering the data and enable the rapid measurement of key parameters over wide areas without disturbing the object under observation. The nature or scales of occurrence of other necessary observations require that in-situ measurements be made. In both cases technology exists or is being developed but its application needs to be integrated and extended from local, specific case studies, often using experimental systems, to global operational scenarios based on long-lived sensor deployments. This will have benefits for the Committee on Earth Observation Satellites (CEOS), too, because they will see a significant increase in the use of their data, improving the return on the investment made by their funding bodies.

This final point is important, because it confirms that the challenges are not only technical but also **strategic**. These hazards demand concerted action from integrated, cohesive networks of users, scientists and policy makers. How can they engage with each other and build the geohazards community? What are the barriers to global application of local best practice? Will solutions that work in the developed world also work in developing countries? This document describes the main components of strategy designed to answer these questions as well as to make sure that the necessary observations are made. It is therefore aimed at both the international geohazards user community who manage the problem and the IGOS partners who make the observations. The strategy's objective is to integrate dispersed, multidisciplinary and applied research into future cohesive, operational systems by filling observational, organisational and knowledge gaps over the next decade. The benefits will include: maximising returns on investments made by international agencies, through optimised use of the resulting observations; linkage of established in-situ monitoring systems with new EO techniques; coordination of activities and observations; and the development of a coherent, well-informed global geohazards community to address the underlying issues.

These missing pieces of the jigsaw can best be provided not through an isolated approach for the geohazards, but rather through developing a place for geohazards in the Integrated Global Observing Strategy. The IGOS Partnership brings together the key international agencies that make and use global observations, either from space or on the ground. It provides a coordination mechanism to support the integration of these observations, as well as the communities that work with them. Its long-term aim is to put in place all the pieces necessary for the IGOS to become a reality. Progress towards that aim is being pursued by developing a cohesive set of strategies on well-focused themes, such as the Oceans and the Carbon Cycle. It is the ideal framework within which to address the deficiencies in current approaches to the geohazards issue, avoiding overlap but ensuring that the key gaps are filled. The other Themes were used as guidance in preparing the Geohazards Theme, which the IGOS partners had proposed in 2001 and approved in 2002. The Theme Team has now developed the strategy to the point where this report describing its key features can be issued.

CONTEXT AND SCOPE

For the strategy to be capable of implementation, it is necessary to clearly set out the scope of this IGOS theme, defining its place alongside other initiatives. The UN's now completed IDNDR, culminating in the current International Strategy for Disaster Reduction, forms a framework for action to which this proposal is intended to respond. The starting point for the necessary technical development is the work of the CEOS Disaster Management Support Group (DMSG), on whose foundations this strategy builds and whose members helped write it. That group has considered the whole range of natural disasters and documented appropriate responses to them, especially in terms of EO data. So, this strategy takes forward a coherent subset of DMSG recommendations covering the geohazards specifically, leaving floods, fire, ice and oil spills to other initiatives. The aim is to provide a unique, coherent IGOS theme on geological and geophysical hazards.

What provides this cohesion? Each geohazard is a response to a specific set of geological and environmental conditions, but there is a common Earth system process linking all such geological and geophysical hazards: deformation of the Earth's crust. This means that similar observational and modelling techniques can be used to address all three geohazards. These do not apply so well to hazards involving different surface processes, even those with a geological root like tsunamis. The interaction of earthquakes, submarine landslides and the oceans to produce tsunamis is an area of potential cooperation with the IGOS ocean theme and with NOAA geohazards related services available on their National Geophysical Data Center (NGDS). The strategy aims to strike a balance between the many common aspects of the geohazards that make this a coherent theme and individual characteristics that are also important. This is achieved by considering the user needs for each geohazards separately in Chapter 2 before drawing out the common observational requirements in Chapter 3. The strategy then places most emphasis on the common needs whilst allowing the specific needs of a particular hazard to be addressed wherever necessary.

The scope must also be limited in terms of the type of response to these hazards. Disaster management and damage assessment are already being addressed by initiatives such as the UN Action Team on Disaster Management and the International Charter on Space and Major Disasters. The Action Team is tasked with implementing, through international cooperation, an integrated global system to manage natural disaster mitigation, relief and prevention efforts through EO and other space-related services, making maximum use of existing capabilities and filling gaps to provide world wide coverage. The Charter aims to provide a unified system of space data acquisition and delivery for users affected by disasters, to promote cooperation between space agencies and space system operators and to allow their participation in the organisation of emergency assistance. Both cover a wide range of disasters and in practice emphasise the disaster response element. The geohazards IGOS is restricted to geological hazards and emphasises the preparedness element.

The strategy proposed here is to develop close links with all these complementary initiatives through cross-membership and only cover in detail those activities where there is a unique gap that needs addressing. This means that the focus of the geohazards theme is on disaster preparedness rather than crisis response. It includes work such as assessing the spatial and temporal distribution of these hazards, expanding the means of monitoring them, improving data management and developing better models, so as to produce more comprehensive management plans, information and reports in support of improved mitigation. The aim of these processes is to improve our capability to forecast the hazard's behaviour and ultimately to predict their occurrence reliably. Within this scope, these developments will make an underpinning contribution to crisis response through the related initiatives, for example resulting in products that form a starting point for damage mapping. Similarly, the strategy does not address risk directly. This requires a consideration not just of the hazard but also of the value of the economic activity and infrastructure exposed to the hazard - a volcano on Mars may be hazardous and yet pose no risk to someone on Earth. An entirely different community carries out this type of assessment. Nevertheless, the information products arising from the geohazards IGOS will form an input to such risk assessment procedures by characterising the hazard that creates the risk.

GOAL AND STRATEGIC OBJECTIVES

Despite much valuable work being done through existing initiatives, there is still a lack of integration, key observations are not available, approaches are often local rather than global in scale and there is no overarching framework to pull all these initiatives in the same direction. This means that the geohazards community, the observations made to manage geohazards and the science needed to understand them are in a transitional state between research and operations. The goal of the geohazards IGOS is therefore to integrate disparate, multidisciplinary, applied research into global, operational systems by filling gaps in organisation, observation and knowledge over the next decade. In order to achieve this, the IGOS Geohazards Theme has the following four strategic objectives:

- **Building capacity**: engage and build the global geohazards community, so as to achieve the best from the human as well as the technological resources available to address this issue, ensuring that users needs are fully explored, understood, documented and acted on;
- **Observations**: put in place systems to deliver reliable, cost-effective and sustainable satellite and ground-based observations that make best use of existing tools, help define and take advantage of emerging technologies and meet the observational needs of the geohazards user community globally;
- **Integration**: ensure that end users and scientists work together to define information needs, extract the maximum value from existing, planned and future observations by using EO and ground-based systems in concert, and develop GIS and modelling technologies that integrate these data into geohazards information products that meet the stated needs; and
- **Promotion**: develop education, sharing of data and information, knowledge and know-how, global databases and networks, and knowledge and skills transfer to the developing world, thereby increasing the capacity of all countries to manage risk related to geohazards.

The strategy's impact will be judged not only by how many new satellites result but also by the degree of technical integration achieved and the extent to which the more intangible, human elements are put in place. The benefits may be hard to predict but the costs of not acting are clear. It is salutary to examine the benefits derived from over three decades of global ocean observations. In addition to all the obvious benefits related to navigation and other marine operations, this investment has delivered major scientific advances such as the measurement and understanding of El-Ninjo. These advances in knowledge have transformed our understanding of how the oceans work in such a way, and with such benefits, that could not have been foreseen during the initial phase of investment. The geohazards IGOS has hopes that the provision of long-term continuity in geohazard observations will have a similar impact, perhaps ultimately even in terms of prediction. The impact must therefore be sought in the statistics associated with the phenomenon. If the hazard has been mitigated and, better still, one day predicted reliably, the risk will have been reduced, fewer lives will be lost and the money saved will be flowing to aspects of development ■

The starting point for this geohazards IGOS is to identify those who will benefit from the strategy, its main end users, and other stakeholders who have significant roles to play. These include the citizens affected by the hazards, responsible authorities who need information about geohazards in order to manage them, monitoring services and information providers who integrate basic observations into useful information products, researchers increasing our knowledge about how these hazards behave and the agencies making the critical observations. All these groups have needs that the strategy must address if it is to meet the ultimate needs of the end users, which is to protect their lives and properties from these hazards. It is aimed at end-users, scientific users and the IGOS partners in particular.

THE USER COMMUNITY

The populations affected by geohazards globally will be the ultimate beneficiaries of this strategy. More accessible and improved geohazards information will improve both the citizen's preparedness for such hazards and the effectiveness of society as a whole in responding to major disasters. However, these ultimate beneficiaries will not be instrumental in developing and delivering that information or in deciding how to act upon it. The critical users specifically targeted by this strategy are those who will do that as part of their professional duties, on behalf of the public at large. These users of geohazards information and observations fall into three critical classes, according to their different roles and consequent needs and these are described below. They would all benefit from a successful geohazards IGOS. Other stakeholders include those who supply the observations required by these users, as well as to those concerned with information dissemination.

The key end users are the **Responsible Authorities**. This group are responding to the drivers set out in Chapter 1 and are the primary consumers of geohazard information. They use it to manage geohazards on a day-to-day basis, to issue public alerts and to make ongoing assessments of evolving hazards. The group includes a wide range of government officials at the national, regional or local level. It includes elected officials and representatives, emergency managers, police and fire officials, civil defence or military personnel, staff of NGOs and land use planners. The role of this group is crucial to the successful mitigation of loss of life and property. They decide when and where to evacuate threatened areas and provide shelter, food, and water for the displaced population. In addition, these bodies interact with a range of other end-users that include insurance companies, engineering and construction companies, mining and exploration companies, and infrastructure operators in the public and private sectors as appropriate. All these users generally need derived information products rather than the raw data on which they are based. They are interested in the long-term identification of geohazards, to support their role in long-term hazard mitigation through their control of, influence on or implementation of land-use planning decisions. But they also need short term "near real time" information whenever a hazard looks like becoming a disaster. Their needs have led to development of those monitoring systems that exist today.

The second group of critical users are **Scientists in Monitoring and Advisory Agencies**. These vital, intermediary users provide the primary information products that support the decisions made by the responsible authorities. The group includes scientists who are directly responsible for monitoring specific geohazards in the long term, for synthesizing the available data into information and for providing continuously updated assessments of the phenomenon monitored and the hazards it poses, so long as the activity continues. These scientists are found in national geologic surveys, running seismic networks and staffing volcano observatories. They have a mandate to monitor a specific type of geohazard, often within a defined geographic area, and are responsible for the maintenance of monitoring devices making in-situ observations. This group uses and integrates data daily and is the contact point with the local civil authorities during a geohazards-related emergency, when they provide interpretations and recommendations directly to those authorities. They may also work with key specialists in the private sector who have an expertise in the production of certain types of value added product. At the same time, they may carry out research, especially when the hazard they monitor is less active, and pursue long-term mitigation as well as short-term crisis response.

The third group of critical users comprises **Research Scientists** doing research that may improve our understanding of the geohazard, ability to mitigate its effects and capacity to forecast events. Research into geohazards is usually performed in universities and large public laboratories, but a number of private sector organisations also have important roles to play. There is often overlap with the second group, who typically apply research findings as they emerge and provide feedback on their effectiveness on the ground. The key difference is that these researchers do not normally have a specific mandate for studying, analysing or monitoring the geohazard. Their host institutions rarely run operational monitoring networks providing information on a daily basis. Consequently, there is a real difference between the basic research done by this group, and the continuous monitoring and synthesis performed by their colleagues in the monitoring and advisory agencies. This leads to somewhat different needs and perspectives, but the two groups are close enough that scientists may move between them several times over the course of their careers.

Beyond the immediate user community there are other important stakeholders to consider. The supply of basic Earth Science data is critical to all users. Agencies and commercial operators that collect and distribute EO imagery of the earth's surface, or that enable data collection from airborne and in-situ platforms, or that provide communications facilities all have a role to play. Organisations that provide and support facilities for operational monitoring and research campaigns on geohazards are a vital partner. International groups, especially the IGOS Partners who will support and oversee the implementation of this strategy, play an important integrating role. A priority for the geohazards IGOS will be to suggest ways for the supply side agencies to facilitate more effective transfer and continuity of in-situ and space-borne data to the scientists monitoring and researching individual geohazards.

Finally, the media are an important player, having a strong influence on successful responses to events. They convey the messages, alerts and reports, but are not truly users of the information. Their most critical role is to relay the decisions of the emergency managers and decision makers in responsible agencies to the population at risk. The media also transmit information from monitoring and advisory agencies to the public. Groups 1 and 2 must communicate directly with each other, and coordinate their messages, so that information released to the public through the media is clear and consistent. The article on "Professional conduct of scientists during volcanic crises" (IAVCEI, 1999) provides an excellent overview of this process and other communication issues that arise during volcanic crises in particular. There are educational aspects to geological hazards that also require the main users to speak to the public with one voice.

NEEDS FOR INFORMATION

There is a common set of questions to which all beneficiaries, users and stakeholders need answers: the most important are what will happen, where, when, how and what will be the duration and the extent of the affected area. The answers vary depending on the user's category and on the type of geohazard and may imply very different time-scales. Unfortunately it is not possible to give firm answers to most of these questions: the gap between what is known and the knowledge required to answer these questions, what is observed and what must be observed to provide the information, how well data are integrated compared to the degree of integration needed to make appropriate information products, is still very large. The purpose of the geohazards IGOS is to close that gap by making the best possible use of all available information and by defining clearly the extra information that is required. End-users' needs within each of the three geohazards are analysed in the following sections, but common needs fall into three main categories: an inventory of the hazard to provide a baseline; ongoing monitoring of change against that baseline; and rapid supply of information during a crisis.

VOLCANIC HAZARDS

What the various users need in detail is dictated by the nature of volcanoes and volcanic eruptions. Key features peculiar to volcanic unrest and activity are that:

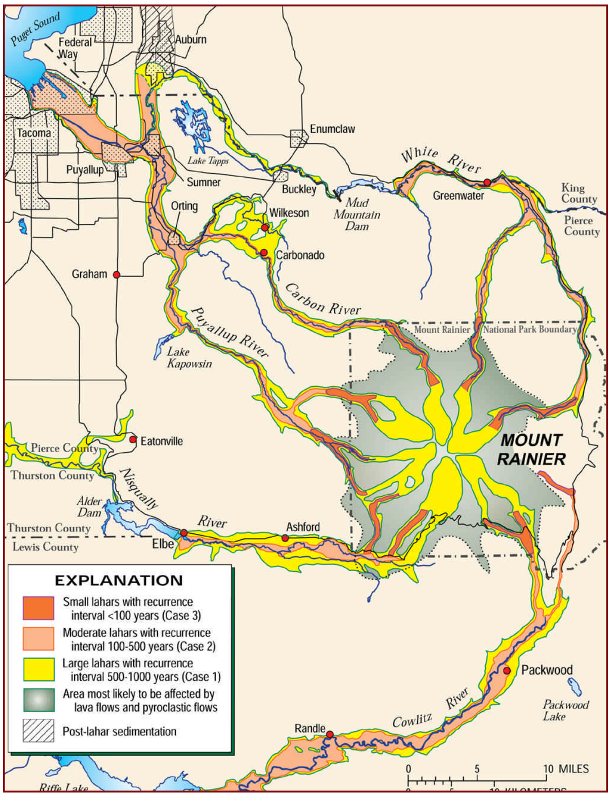
1. Scientists know where the problematic volcanoes are. Volcanoes usually give some warning of impending eruptions, the signals of which are detectable if appropriate monitoring is occurring. This contrasts with earthquakes and landslides, where detailed location and times of events cannot be predicted.
2. The basic technique for minimizing loss of life and property is to move out of the way, or to build out of reach of the volcano. There are no foreseeable advances in technology that will change this: it is not possible to prevent a volcanic eruption from happening and large eruptions are sufficiently rare that it is difficult to anticipate their consequences.
3. Volcanic hazards vary from one volcano to another, and from one eruption to the next. The big killers are pyroclastic flows, lahars, and tsunamis triggered by volcanic eruptions (Blong, 1984). The most frequent lethal events are tephra explosions (Simkin and other, 2001). The longest-lasting damage is usually inflicted by thick lava flows or major collapses of volcanic edifices, as at Mt. St. Helens in 1980.
4. Eruptions leave traces in the geologic record, allowing reconstruction of the eruptive history (frequency, type of eruption, size of eruptions, ages of eruptions) of a volcano. This gives some indication of what the next eruption at a given volcano will be like.

The needs of the three groups of critical volcanic hazards users are summarized broadly in Table 1. The end users in the responsible authorities need information, not data, whether for crisis response or long-term mitigation via land-use planning. The other two groups of users need data to create information products and undertake research. The research scientists will produce more detailed models and work over longer time periods than the scientists in the monitoring and advisory agencies. Between them they are responsible for producing the interpretations and models needed by the end users. The needs are also somewhat different for crisis response compared to monitoring and mitigation.

When volcanic unrest or activity occurs, the civil authorities need clear information and interpretations of all aspects of the activity that are either relevant to the hazard and risk assessments being presented or can be detected by the affected populace. This includes reports of felt earthquakes, visible ground cracking, detectable changes in

TYPE OF USER	NEEDS FOR VOLCANIC CRISIS RESPONSE	NEEDS FOR VOLCANIC HAZARD ASSESSMENTS
Responsible Authorities ("end users")	Clear, authoritative information on most likely course of the unrest/eruption. Timely updates are critical Best guesses on when and what type of eruption, possible size, which areas will be affected and where will be safe.	Hazard zonation maps: paper maps or GIS data bases showing areas of lower vs. higher risk, for future eruptions. The maps for the various major hazards (lava flows, lahars, ash fall, etc.) will be different.
Scientists in monitoring and advisory agencies	All monitoring data relevant to their hazard (seismic, deformation, thermal and gas in particular), collected in real time but accessed when needed. Digital Elevation Models (DEM) and mathematical models to help predict distribution of pyroclastic or lava flows, or lahars, so as to identify both areas of high risk and safe areas	Base maps and DEMs. Maps showing the distribution of all young volcanic deposits, with dates, to determine type, size and recurrence intervals of eruptions over significant time (10,000 years or more). 3D models of volcano structure. Monitoring of deformation, seismicity and other geophysical and geochemical parameters.
Research scientists	All data relevant to their research, collected in real time but accessed when needed. Feedback on the performance of models and scenarios.	Same as above, if research involves detailed geologic mapping of young volcanoes. Continuity of observation of all related geophysical and geochemical data. Feedback on the performance of conceptual models etc.

Table 1: Summary of user needs for volcanic hazard information



Hazard zones for lahars, lava flows, and pyroclastic flows from Mount Rainier. (from Hoblitt and others, 1998; US Geological Survey Open-File Report 98–428)

emissions of SO2, and so on. This latter point is important: even where there is no immediate risk of an eruption, if people can see signs of unrest for themselves, the local authorities need to understand the situation well enough to reassure the public. The stream of information needs to be continuously updated, as events unfold. The scientists responsible for assessing the incoming data may provide scenarios on the likely course of an eruption and how soon it might occur. Based on the prior history of the volcano, they will identify areas that are relatively safe, in the event that evacuations might be needed. Both activities require up-to-date, relatively high-resolution topography for the volcano, in addition to the data streams mentioned above. Once an eruption begins, the flow of information must speed up, as the authorities need to know what will happen next, which areas will be affected, and how thick any volcanic deposits may be. Many additional activities and methods come into play only after an eruption has started. In addition to mapping the activity in real time, observers must note changes in seismic behaviour or deformation patterns, especially any that suggest that the site of the eruption may change from the summit to the flank of the volcano. Such changes need to be recognized and conveyed to the authorities and the public as quickly as possible.

Volcanoes that have been dormant awaken gradually, with the onset of unrest typically occurring weeks or months before an eruption (as happened at Mt. St. Helens (1980), El Chichon (1982), Nevado del Ruiz (1985), and Pinatubo (1991)). Volcanologists know to use this period to raise the awareness of civil authorities and the general public about possible impending events, based on the observed unrest or activity. Their task is easiest where the volcano in question erupts frequently, so that many are familiar with the symptoms and the hazards involved. However, there have been some notable successes even for eruptions at long-dormant volcanoes (Mt. St. Helens, 1980; Pinatubo, 1991: see Newhall and Punongbayan, 1996). In these two cases, success depended on persuading the responsible authorities that the probability of a large eruption was high enough to justify ordering the evacuation of large areas near the volcanoes. Evacuations of people and moveable property resulted in saving thousands to tens of thousands of lives and millions of dollars in property damage.

Whilst it is such immediate crises that create the dominant user need, this need can only be addressed if attention is also paid to longer-term planning and mitigation of volcanic hazards. The principal tool for this is the volcano hazard zonation map. Volcanologists prepare these specialized maps for the end users and the general public. They show, with a different map for each hazard, the areas at risk and their susceptibility to the hazard in question. The probability of occurrence may be classified as simply high-moderate-low, or it may be more quantitative. Before a hazard zonation map can be prepared, scientists must have a geologic map of the volcano and all of its youngest products. To produce such a map involves determining the areas covered by each eruption, the type of materials produced, and the ages of all young eruptions, going back at least 10,000 years. This information defines the eruptive style and history of the volcano, the frequency of its eruptions, and its characteristic repose period. Beyond the geologic and hazard zonation maps, most longer-term mitigation efforts require other kinds of information, such as process research, the development of 3D and mathematical models of volcano structure and behaviour or new instrumentation. Mitigation of volcanic hazards over the longer term, in the absence of volcanic unrest and an impending eruption, is a complex scientific and social project.

EARTHQUAKE HAZARDS

Characteristic features of earthquakes that are relevant to user needs include:

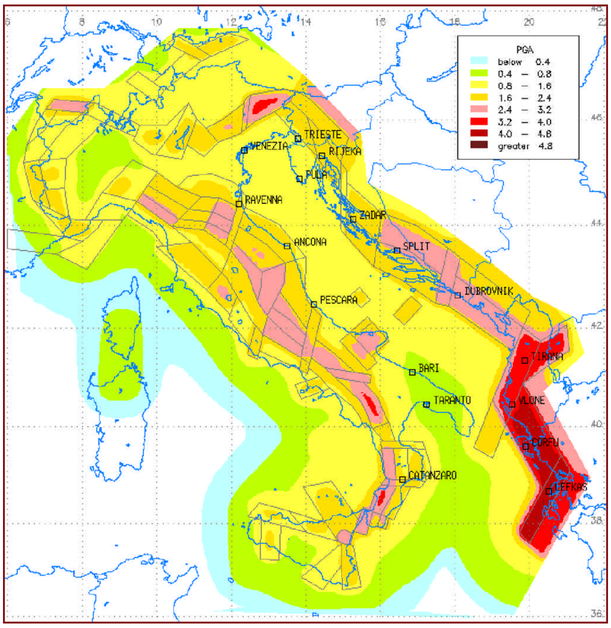
1. the epicentres of large earthquakes are usually located along known seismically active zones, although the disruptive effects of an earthquake may extend over areas 100s of kilometres away;
2. the ground shaking hazard decreases with distance from the epicentre, but it may be strongly amplified in areas underlain by weak materials such as unconsolidated sediments;
3. the most evident effect of an earthquake is a conspicuous lateral or vertical displacement along the active fault, which is usually recorded in the geology and geomorphology of an area;
4. earthquakes may cause landslides or areas of liquefaction that are preserved;
5. all these landscape features can be mapped in detail and used to reconstruct the palaeoseismicity of an area, allowing the identification of probable active seismic zones even where there is little historic record of large earthquakes.

As in the case of volcanoes and ground instability, the needs of the three critical categories of users can be analysed from the point of view of inputs needed for hazard mapping as well as rapid responses to specific earthquake events (Table 2).

Once earthquakes occur, the most pressing need is for information on the location and magnitude of the event and the likely timeframe of the aftershock sequence. Because there is a time lag between arrival of the first seismic wave (the P-wave) and the more destructive shear and surface waves, it is possible, in favourable circumstances, to issue up to tens of seconds of warning of the arrival of the later waves. Given rapid (or fully automatic) communication systems, such information could be used to trigger emergency mitigation activities, such as stopping trains, shutting down nuclear facilities or parts of an electric power grid, and so on. Few such systems exist at present but they have been tried out in Japan and Mexico. A product that is more widely needed, and can be produced with present systems, is a shake map: this is a map, generated within 5 minutes of a damaging quake, that shows the intensity of ground shaking for the area affected by the particular quake. This product allows more efficient recognition of which areas are likely to have sustained the

TYPE OF USER	NEEDS FOR SEISMIC CRISIS RESPONSE	NEEDS FOR EARTHQUAKE HAZARD MITIGATION
Responsible Authorities ("end users")	Clear, authoritative information on the location and magnitude of the shock and the timeframe (in days) of aftershocks. Timely updates are critical for activating shutdown of critical facilities (power plants, trains, etc.) Post-event maps (shake maps, damaged/ affected areas, identification of safe areas).	Hazard zonation maps: paper maps or GIS data bases showing areas of lower vs. higher intensity of ground motions. The maps for various secondary effect of seismic hazards (landslides, liquefaction etc.) also needed. Ultimate need: reliable prediction of events.
Scientists in monitoring and advisory agencies	All data available, in as near to real-time as possible, on the following in particular: Seismicity, intensity, strain, DEMs, soil type, moisture conditions, infrastructure and population.	Compilation of seismic archives. Base maps (geological, soil, active faults, hydrological, DEMs) and conceptual models. Continuous monitoring of deformation, seismicity and other geophysical and geochemical parameters.
Research scientists	All data relevant to their research, collected in real time but accessed when needed. Feedback on performance of models and scenarios.	Same as above. Continuity of observation of all related geophysical and geochemical data. Feedback on the performance of conceptual models etc.

Table 2 Summary of user needs for earthquake hazard information



Results of the seismic hazard evaluation in the Adria region. Values of PGA in m/sec2 have been computed for a return period T=475 years (corresponding to the 90% non-exceedance probability in 50 years), and taking into account the uncertainty in attenuation. This map was produced by the Global Seismic Hazard Assessment Programme launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR).

most damage, and which areas are zones of relative safety, where facilities should be relatively intact.

Unlike the situation for volcanoes, where we have widely recognized signals of unrest and potential eruption, we lack comparably reliable pre-event signals for earthquakes. Forecasting a hazard depends on the recognition and detection of anomalous precursory phenomena. Because earthquake locations are to date known only after the fact, it has been difficult to define monitoring strategies for any seismically active zone that might confirm the existence of such precursors. Whilst there are candidate phenomena, such as foreshocks, seismic quiescence before strong aftershocks, variation in radon concentration and the temperature or level of groundwater, not all earthquakes are preceded by such phenomena. The recognition and vetting of viable pre-quake phenomena should be a major target on the agenda for earthquake-related research.

In contrast, significant benefit can be gained from preparatory mitigation. The key product that end users need is a seismic hazard zonation map, which shows the relative intensity of ground shaking expected. Earthquake catalogues are used by monitoring services and research scientists as a first input to provide such hazard mapping alongside local geological and geomorphological mapping. Spatial and temporal patterns of deformation are derived from historic data in seismic archives, paleoseismology, and space- and ground-based surveys. Structures associated with the earthquake are inferred by analysis of seismicity, based on geophysical information, and geological, soils and structural mapping. The combination of these types of information with terrain models enables the creation of detailed seismic hazard maps. These maps provide the basis for appropriate decisions on land use, building standards and the specification of structural engineering for major infrastructure. Where is a large population in an area of high seismicity, there is a need for local networks of seismometers (especially strong-motion detectors), for regional Global Positioning System (GPS) networks, and for strain detectors in critical locations.

GROUND INSTABILITY HAZARDS

Ground instability encompasses a wide variety of surface deformations driven by surficial processes and shallow crustal phenomena, the two main sub-categories of which are landslides and ground subsidence. The key points of interest when analysing ground instability may be expressed as follows:

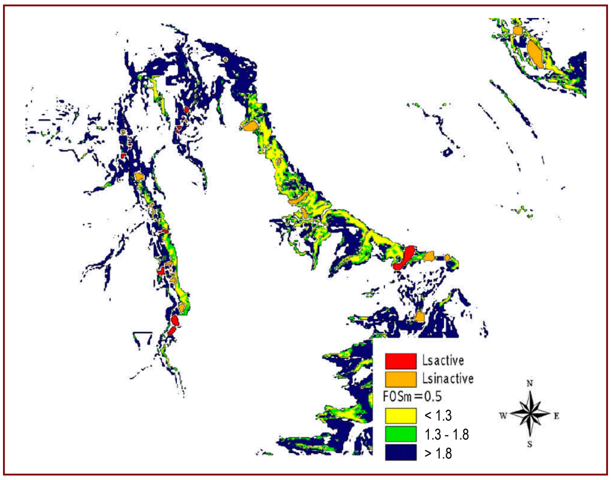
1. Ground instability is one of the main processes by which landscapes evolve and so the related hazards result in a complex, changing landscape that must be mapped and understood in detail in order to assess its future behaviour.
2. Ground instabilities vary enormously in their distribution in space and time, the amounts of energy produced during the activity and especially in size. This means that the resulting surface deformation varies considerably from one type of instability to another.
3. Individual ground instabilities are local landscape phenomena. Data about "local" conditions must be available in order to associate the identified deformation patterns with causative factors and hence model zones of different degrees of susceptibility to the specific type of ground instability hazard.
4. Collectively, individual ground instabilities may have a common trigger, such as an extreme rainfall event, and therefore occur alongside many equivalent occurrences over a large area. This means that they can have a significant regional impact.
5. Ground instability hazard analysis is interdisciplinary, involving geotechnics, geomorphology, geophysics, hydrology, hydrogeology, solid and fluid mechanics and various information sciences.
6. Ground instabilities, even when catastrophic, tend to evolve to become progressive failures: once they start, there is a high probability that they will develop further in space and time.

The three main categories of users and their corresponding needs are shown in Table 3.

Determining where, when and to which extent ground instabilities will take place is a short-term requirement as far as the safety of exposed people is concerned. These questions are easier to answer for subsidence than they are for landslides. The mechanics of subsidence are better understood and, once the phenomenon has been triggered, its evolution can be modelled and hence predicted with some accuracy. Triggers

TYPE OF USER	NEEDS FOR CRISIS RESPONSE	NEEDS FOR HAZARD MITIGATION
Responsible Authorities ("end users")	Local rapid mapping of affected areas, magnitude of instability, updated scenarios during ongoing instability, impact analysis. Early warning information.	Regularly updated susceptibility and hazard zonation maps: landslides, debris flows, rock falls, subsidence. (at scales as appropriate) Ground instability scenarios.
Scientists in monitoring and advisory agencies	Near real-time observational tools As for mitigation, plus seismic data, weather forecasts.	Data on landslide inventory, DEM, deformation (to the ground and critical infrastructure), hydrology, geology, soils, geophysical, geotechnical, climatic, seismic zonation maps, land cover, land use, historical archives, relevant human activities (at scales as appropriate) Regular and consistent observations. Methods and models for susceptibility and hazard evaluation Data from well-observed past events.
Research scientists	As for mitigation. Feedback on performance of scenarios and models.	Continuity of observations, appropriate data as above for understanding processes and for development of models and observational tools Access to other scientific information Data from well-observed past events

Table 3: Summary of user needs for ground instability hazards information



Landslide susceptibility map using a regional physical-based modelling approach for the Bonn area. (Note: Inactive and active landslides refer to the activity of respective locations. FOS m=0.5 refers to the Factor of Safety using the Infinite Slope Model and applying a 0.5 ratio of water table depth to regolith thickness. For additional security in engineering applications, FOS are classed below 1.3 as 'unstable', FOS between 1.3 and 1.8 as 'marginal stable', and FOS > 1.8 as 'stable'. From Mouline-Richard & Glade 2003.

are also better understood; removing a certain amount subsurface material results in a predictable amount of subsidence and size of area affected. Landslides are a less regularised motion and have complex, highly variable triggers. Predicting when this type of failure will happen is conceivably the most difficult challenge for the relevant scientists. Major landslide disasters, such as the Vajont in 1963 (1,900 fatalities - AVI database) and Caracas in 1999 (19,000 fatalities - USGS), can be every bit as devastating to society as volcanoes or earthquakes. Large landslide and debris flow disasters triggered by extreme weather are more frequent than volcanic eruptions and about as common as earthquakes. They may be preceded by precursory evidence of landslide movement such as appearance of cracks, accelerating movement, or increased rock-fall activity.

Appropriate real time monitoring of known landslide hazards, transmitting a continuous stream of information to remote control stations and alert systems, can play a crucial role. Movement detectors can be used to issue alerts any time the movement rate increases. The threshold for the alert to be issued is generally computed as the acceleration or the measured deformation versus a theoretical model that has been developed for the specific hazard. Other techniques for early warning systems focus on the triggers rather than on the deformations: in this case a sound model generally based on hydrologic forecasting is also needed and, for a defined rainfall threshold, alerts can be issued. But due to the amount of information to be collected, processed and analysed, early warning based on site-specific analyses is not practical for large areas. Thus, a two-fold strategy of spatial susceptibility and hazard mapping coupled with monitoring of the most hazardous zones offers the best hope of providing useful information, on which the responsible authorities can base both informed land-use decisions and then evacuation plans and responses during a crisis.

So, underpinning efforts on early warning of specific events, end users need simple, qualitative information concerning the longer-term threats posed by the geohazard so that they can mitigate them. Depending on the extension of the area, such information may be provided in susceptibility and hazard maps. Areas with present or past ground instability must be identified and classified. Within active landslide and subsidence zones, the extent and pattern of surface deformation must be investigated by the monitoring or advisory service. A clear knowledge of the location and evolution of the phenomenon in space and in time is a fundamental step towards correlation of the geohazard with its causative/triggering factors. These must be identified and can be natural or anthropogenic. Factors of natural origin embrace a wide range of phenomena such as geodynamics (e.g. earthquakes, volcanic eruptions) and climate (e.g. rain, snowmelt, erosion, floods). The human actions that may result in ground instabilities include: excavation, slope modification, deforestation, irrigation, and the extraction of minerals, fluids and gases from the subsurface. Identification of the processes and mechanisms responsible for loss of strength and leading to instability is the main step for comprehension and therefore mitigation of ground failure. Once the processes and mechanisms are identified, it is possible to establish physical and mathematical models.

There is a dearth of sensitivity analysis of existing predictive models and the relative influence of key physical quantities remain to be identified. The development of such models is critical in supporting production of landslide or subsidence hazard susceptibility maps. Associations between the deformation observed and the causative and triggering factors can be made empirically, through statistical analysis or within geotechnical models. The type of analytic tool used depends on the working scale, on the application goal and on the variety, quality and resolution of available data ■

The previous chapter examined the needs of the end users in particular for information products.
This chapter describes the observations required by those in monitoring and advisory agencies and undertaking related scientific research in order to meet users' needs for information. Commonalities in requirement between the three main hazards are emphasised and form the basis for a common approach in the rest of the report. Some of the key observation systems are also described.

The information products and advice required to support decision-making by end users in responsible authorities are based on a wide range of observations. Some are satellite-based, some made by aircraft and many are measured by critical ground-based systems. Because there is no way that events such as earthquakes and volcanic eruptions can actually be prevented, the emphasis here is on observations made between events that permit better forecasting and mitigation planning. Scientists in monitoring and

REQUIRED OBSERVATIONS	BACKGROUND MONITORING/ASSESSMENT	CRISIS RESPONSE
Characterize **seismicity** of volcano or group of volcanoes [magnitude, 3-D location, and type of earthquake(s)]	Individual volcanoes require 3-6 seismometers, enough to detect and locate earthquakes of Magnitude 0.5, data relayed and processed in real time	Repairs as needed and feasible
	Regional network good enough to detect and locate quakes of Magnitude 2.5, data relayed and processed in real time	Additional stations, deployed near or on the volcano, to detect and locate earthquakes of Magnitude 0.5
Characterize **baseline topography** and ongoing **deformation** of volcanic edifice (horizontal and vertical); monitor changes in gravity; determine location of faults, landslides and ground fractures	EDM and/or GPS network of stations, either continuously transmitting or reoccupied as necessary	Additional GPS stations as needed to capture deformation; more frequent occupation (if data not continuously transmitted)
	Leveling and tilt networks surveyed as needed Borehole strainmeters (continuous recording) Gravity surveys (1-5 years)	More frequent occupation (if not continuously recorded and transmitted)
	SAR interferometry (1-5 years, depending on the volcano's historic activity)	Request more frequent tasking plus search data archives for additional possible image pairs. Use terrestrial interferometry.
	Map existing geologic structures on volcanoes using high spatial resolution satellite and aerial surveys and geological and geophysical ground surveys as needed.	Request repeat overflights to check for new cracks; possibly install strainmeters across selected cracks
Characterise **gas** and ash emissions of volcanoes by species (SO_2, CO_2) and flux (tons per day)	COSPEC, LICOR surveys at regular intervals (weekly, monthly or annually)	More frequent surveys, perhaps using small aircraft if plume not accessible by road
	Routine checks of appropriate satellite imagery (GOME, SCIAMACHY, TOMS, ATSR, AATSR, AVHRR, MODIS, MISR, MERIS, ASTER, SEVIRI, etc.)	Additional requests tasking for higher-resolution data, check archives for useable imagery
Characterize and monitor **thermal** features of volcanoes (their nature, location, temperature, possibly heat flux)	Map and monitor hot springs, fumaroles, summit craters, crater lakes, and fissure systems for temperature variations using ground-based instruments and high spatial resolution satellite data (SPOT, Landsat, ASTER)	More frequent observations, including visible and IR photography and pyrometry as appropriate
	Systematic acquisition and analysis of time series of IR, TIR and MIR imagery from airborne digital IR camera, moderate resolution (e.g. ATSR, AATSR, AVHRR, SEVIRI, GOES, GMS) to higher-resolution (e.g. ASTER, MODIS) satellite imagery for thermal background characterisation.	More frequent overflights with digital IR camera; additional requests tasking for higher resolution data (Landsat, ASTER, other), check archives for time series of thermal data.
Characterize **eruptive style** and eruptive history of volcanoes	Characterize, map and date all young eruptive deposits of the volcano	Observe eruption columns, plumes and surficial deposits (using overflights with visible and IR photography, video). Monitor their motions (speed, direction, areas covered and threatened), character, and thickness. Update maps.

Table 4: Volcanic hazard observations most required and the best available observational systems

REQUIRED OBSERVATIONS	BACKGROUND MONITORING/ASSESSMENT	CRISIS RESPONSE
Characterize **seismicity** of seismically active region (magnitude, 3-D location, and type of earthquake(s))	Global monitoring network able to characterize earthquakes of Magnitude 3.5 with data relayed and processed in real time	Network is in place, developed to verify the Comprehensive Test Ban Treaty. No specific action needed.
	Regional network of strong-motion detectors, capable of surviving ground motions	If none deployed, add stations afterward to capture aftershock sequence
Characterize **baseline topography** and ongoing **deformation** of region (horizontal and vertical)	EDM and/or GPS network of stations, either continuously transmitting or reoccupied as necessary	Additional GPS stations as needed to capture post-earthquake deformation; more frequent occupation (if data not continuously transmitted)
	Borehole strain meters (continuous recording) Strain meters on critical structures such as dams, bridges, etc.	More frequent occupation (if not continuously recorded and transmitted); additional strain meters on critical structures to monitor their structural integrity during aftershock sequence
	SAR interferometry (1-5 years, depending on the region's historic seismicity)	Request more frequent tasking plus search archives for additional possible image pairs
Characterize **thermal** signature of region	Obtain and process time series of low/medium resolution IR imagery from polar (e.g. ATSR, AATSR, AVHRR, MODIS) and geostationary (METEOSAT/MSG, GOES, GMS) satellites for thermal background characterisation.	Evaluate time series for possible thermal anomalies before and after the earthquake
Determine location of **faults, landslides and ground fractures** Characterize historic seismicity and paleoseismicity of region	Map existing structures in the region using high spatial resolution satellite and airborne imagery and geological and geophysical ground surveys. Study and date features that provide evidence for major prehistoric earthquakes.	Request over-flights to check extent of ground breaking and offset, for new cracks, landslides, patterns of liquefaction and building collapse, etc.

Table 5: Earthquake hazard observations most required and the best available observational systems

advisory agencies take these observations, integrate and assimilate them and use them in models of critical Earth system processes to produce hazard maps, scenarios and forecasts that answer questions such as: how do the relevant Earth system processes operate; what are the main hazards in a particular case; which areas are exposed to the biggest hazard and which are safe; what is our best estimate of the timing, duration and extent of activity?

The geohazards IGOS has identified a wide range of observations that are required to answer these questions and mitigate each of the main geohazards effectively. This inventory builds on previous works, in particular the reports on EO requirements for earthquakes, volcanoes and landslides presented in the CEOS DMSG final report. The observations have been documented and could be added to the observational requirements database maintained by the World Meteorology Organisation (WMO) on behalf of the IGOS Partners. This strategy summarises the most important parameters to observe in tables 4-6 below covering volcanoes, earthquakes and ground instability and describes key systems that support both monitoring and ultimately crisis response. From this, a set of common requirements emerges that support integration across all three hazards.

> Volcanic Hazards

Volcanic hazard mitigation requires a wide variety of information. Essential volcano monitoring includes analysis of data on the volcano's seismicity, surface deformation, gas emissions and high temperature features. In addition, detailed topography and geologic mapping are required for complete volcano hazards assessments.

> Earthquake Hazards

Earthquake hazard mitigation also requires monitoring of seismicity and deformation, albeit with a slightly different focus and scale than for volcanoes. Geologic mapping for earthquake mitigation emphasizes the mapping of structures like faults. The possibility of surface temperature anomalies or distinctive soil gas anomalies should also be evaluated.

REQUIRED OBSERVATIONS	BACKGROUND MONITORING/ASSESSMENT	CRISIS RESPONSE
Characterise deformation with high accuracy and frequency (horizontal and vertical)	GPS network of stations continuously transmitting or reoccupied as necessary	Additional GPS stations as needed to capture deformation More frequent occupation (if data not continuously transmitted)
	Satellite, airborne and ground-based SAR interferometry at various wavelengths Frequency depending on the type of ground instability (1 month to 1 year)	Request more frequent tasking plus search archives for additional possible image pairs
	Other surveys e.g. levelling, laser scanning (terrestrial/airborne), aerial photography and high resolution stereo satellite data for use in photogrammetry, borehole inclinometers. Frequency depending on the type of ground instability (1 month to 1 year)	More frequent occupation of all ground-based instrumentation (if data not continuously recorded and transmitted). Terrestrial interferometry at a frequency depending on the type and velocity of ground motion.
Topography / Elevation (incl. slope angle, slope length, slope position)	High quality DEM from Laserscanning, photogrammetry or high resolution satellite Regular updated when necessary	Rapid local update needed of how the landscape has changed.
Soil strength parameters and physical properties (incl. clay mineralogy, weathering, soil moisture)	Geotechnical in-situ and laboratory tests inclinometers, penetrometers, and piezometers. Tomographic subsurface surveys. Physical properties of soils, triaxial tests, odometers test as required by modelling process	Request more frequent observations and if possible continuous recording of soil moisture.
Climate Trigger precipitation (rainfall, snow, magnitude, intensity, duration) temperature	Meteo data field measurements Meteorological satellites data	Continuous recording
Seismic trigger magnitude, intensity, duration, peak acceleration, Decay of shaking level with source distance (source, propagation shaking and site effects)	Accelometer network monitoring (Frequency: continuous or reoccupied as necessary) Pseudo-static stability models Dynamic instability models Update as needed	Continuous recording

Table 6: Ground instability hazard observations most required and the best available observational systems

> Ground Instability Hazards

Ground instability hazard mitigation requires a slightly wider range of observations, including geological and soils mapping, topography analysed as elevation, slope and aspect, deformation, climatic and meteorological parameters and seismicity. In many cases the focus is on superficial geology in particular and again the scale is typically regional.

COMMON OBSERVATIONAL REQUIREMENTS

It is clear that observational requirements form a strong link between the three main geohazards. From this point in the strategy onward, it becomes possible to consider them as a whole. This emphasises the coherent nature of the geohazards IGOS theme. Doing so results in four important, common observational requirements:

> Topography

Detailed topographic data is required to analyse all three hazards. Such data are critical to the modelling of any gravity-driven process, such as the emplacement of a lava flow or the progress of a landslide. They also form a key requirement in the subsequent analysis of deformation, providing the baseline against which to measure topographic change. The basic requirement is for a digital terrain model, from which elevation, slope and aspect can be calculated. For volcanic hazards this will typically be at a moderate resolution and for earthquakes it can usually be at a low, regional resolution, as it will be used on a regional basis. The most detail is required for certain types of ground instability, especially small landslides, whose recognition during the inventory stage relies in large part on a landform analysis at around 1:10,000 scale and requires a vertical resolution of better than 1m.

> Deformation

All three hazards deform the Earth's crust. The requirement is to measure topographic changes that can be both sudden, due to catastrophic events, and more gradual, due to ongoing processes. The inflation of a volcano during recharge of its magma chamber, the subtle build up and release of strain between earthquakes, gradual down-warping over a sinking water table: all these motions can be on the order of millimetres, in either horizontal or vertical planes, over a period of days, months or even years. There is good evidence that these small motions are the precursor to more significant deformation and so they must be observed, despite their magnitude, if hazard forecasts are to be improved.

> Seismicity

Seismic activity is a feature of all three hazards. For volcanic and earthquake hazards, it is perhaps the critical observation required to characterise the type and behaviour of the hazard. It is needed in order to describe the hazards' magnitude and location in three dimensions in the subsurface, being one of the few reliable tools that can be used to sense what is happening at depth and so define the plumbing inside a volcano, or the position of subsurface faults. It is also important in ground instability assessment, however, because seismicity is one of the main triggers for landslides in some geological settings, especially mountainous terrain near active plate boundaries like that found in Papua New Guinea. It can generate liquefaction and is also associated with some subsidence phenomena. On a regional scale, its detection needs to be reliable at magnitudes of 2.5 and above, while for individual hazards this increases to magnitude 0.5.

> Mapping

All three hazards require various types of mapping based on EO imagery, aerial photography and fieldwork. Terrain analysis in three dimensions both on the ground and using remote sensing data is used to map landform, geology, structure and soils, based on either a terrain model or stereography. For volcanoes the mapping will focus on younger eruptive deposits less than 10,000 years old. For earthquakes, the most important features to map are faults and existing fractures. For landslides, soils and superficial deposits are critical and mapping must also result in an inventory of current and historic landslides in the region. Scales vary from regional mapping at 1:50-250,000 to local mapping at 1:5-10,000. Local mapping of individual small landslides requires either 1:10,000 scale stereo aerial photography or stereo EO data with a spatial resolution of 1m.

The climatic and meteorological observations required for ground instability investigation can be met using observations made for other purposes. This leaves three other types of observations that are important for one or more specific hazards:

> Gas Emissions

For volcanic hazards, SO2 and CO2 emissions are critical indicators of volcanic activity and hence the monitoring of these gases plays an important role in forecasts. In addition, these gases are hazards in their own right, so they must be considered in any observation system designed to address volcanic hazards. For earthquakes, there is widespread interest in the possibility that certain gas species may be precursors to earthquakes, but so far these investigations remain in the realm of research.

> Temperature

Volcanic activity is intrinsically a high-temperature phenomenon, so in theory thermal monitoring ought to be useful in forecasting eruptions. The range of temperatures of interest is large, from 30-40 degrees centigrade in hot springs to over 1200 degrees centigrade for lava, and most of the heat sources are small (metres to tens of metres in dimension), so there is at present little consistency in how temperature is monitored. For earthquakes, there are some studies that suggest detectable thermal anomalies exist that are observable in satellite imagery prior to an earthquake. Specific cases are few, but the possibility deserves rigorous evaluation. Temperature has only a marginal place in landslide studies, although it can be used as an indirect indicator for the soil moisture variations that can affect the strength of certain slopes and therefore their susceptibility to landslide initiation. It has no obvious role to play in subsidence observations.

> Physical Properties

For ground instability, understanding the behaviour of the hazard requires the collection of detailed geotechnical information on the physical properties of soils and superficial geological deposits. Measurements that are necessary include moisture content, strain, strength, porosity and pore-water pressure. These data are predominantly gathered on the ground, using a variety of instrumentation at specific hazard sites.

KEY OBSERVATIONAL SYSTEMS

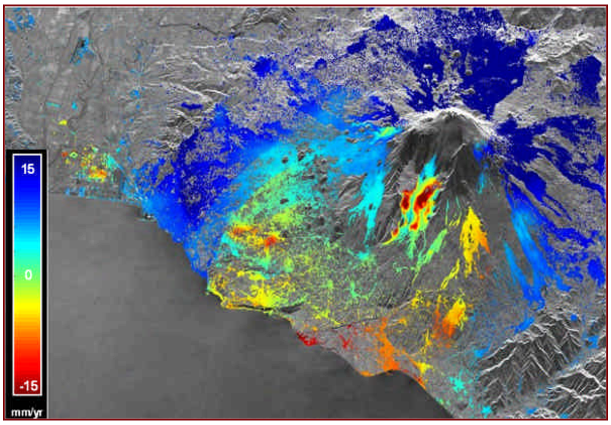
There are current and planned observational systems designed to make various of these observations, including Data Collection Systems (DCS) such as Argos which have been available for more than 25 years and will continue to provide reliable and low-cost observations for years to come. Ground-based observations usually provide high accuracy and are continuous in time but, typically, measurements are only made at specific localities. EO systems are collated in the accompanying tables. They have variable resolution and, typically, provide only periodic observations but with consistent areal coverage over entire regions. Airborne systems are used to gain the advantage of areal coverage offered by EO with either higher resolution or at more suitable times. To get the best spatial, spectral and temporal resolution, a global observing strategy for geohazards must integrate all these data streams. In order to identify any gaps in observations that must be filled by the observing strategy, it is first necessary to document existing and planned observational systems. The following description focuses on the areas with strong commonality between the three main hazards that were identified above.

> Topography

Whilst ground-based methods like traditional surveying and GPS measurements are still used, especially at the site-specific scale under demanding operating conditions, topographic surveying now has a long history of using EO and especially airborne solutions. The most common approach is photogrammetry, initially analogue and now digital, based on scanned analogue and increasingly digital aerial photography. This will remain an important technique, especially at the site-specific scale. Radar altimeters, single-pass airborne radar interferometers and airborne LiDARs are all used to improve available topographic maps and digital elevation models (DEMs). EO sources of topographic data include high-resolution stereo optical satellite imagery, satellite radargrammetry, interferometry and altimetry. The Shuttle Radar Topographic Mapping (SRTM) mission was designed to provide global elevation data, at a baseline resolution of 90m. More detailed resolution and more frequent observations are required in order to document the topographic changes that occur after hazard events.

> Deformation

This is the field of greatest commonality among all three geohazards. Both ground-based and satellite-based techniques are used to monitor ground displacements. Differential GPS networks and terrestrial LiDAR are widely used. They offer high accuracy and continuous observation but they require the installation and maintenance of permanent stations and provide monitoring only at installation points. Tilt, levelling, EDM and strain measurements are also performed in many active volcanic areas, together with other related parameters such as water levels in boreholes (Ewert and Swanson, 1992). Airborne differential LiDAR can make some deformation measurements, but EO solutions are increasingly important. In particular, synthetic aperture radar interferometry (INSAR) is able to detect ground displacements of a few centimetres over wide areas. The frequency of observations is limited the deformation detected is only in the line-of-sight, and it



Application of the multi-interferometric technique of the Permanent Scatterers over Etna. 40 ERS scenes have been used by TRE, a spinoff company of Politecnico di Milano to create this image accounting for average deformations along satellite's line of sight occurred during the time interval 1995-2000. Faults dividing areas characterised by different deformation rates and trend are clearly visible as well as subsidence on the western part of the area. (image courtesy of TRE)

cannot be resolved in three dimensions. The planned COSMO/SkyMed mission aims to provide daily observations by 2007, overcoming limited observational frequency by using a constellation of four satellites (the first is planned for launch in 2005). Existing satellite INSAR instruments are C-band (a wavelength of 5.66cm), offering high resolution, but they only give reliable interferograms for coherent, non-vegetated surfaces. Data from the JERS-1 satellite demonstrated during its lifetime that L-band satellites offer reduced resolution but provide interferograms over a far greater range of surface cover types. The next planned L-band SAR is the Japanese PALSAR on the ALOS satellite, to be launched in spring of 2004. Unfortunately, this instrument is designed to test applications other than interferometry, so it will provide only limited support for deformation analysis.

Other approaches to overcome the problem of limited C-band coherence have been documented in the CEOS DMSG report and include: the use of artificial corner reflectors or active transponders placed in strategic locations; the use of buildings and other strong reflectors as permanent scatterers that can all be identified in time-series of radar images; and the use of ground-based INSAR. Some of these new space-based approaches also allow the removal of atmospheric effects and the construction of deformation histories for each identified point target. INSAR is of critical importance to the success of the geohazards IGOS.

> Seismicity

Seismic monitoring requires networks of ground-based instruments. A global seismic network exists that is capable of locating and characterizing seismic events >M3.5, worldwide (Sykes, 2002). It was installed, in part, to monitor for underground nuclear explosions. The existence of this and other networks mean that locations and magnitudes for large earthquakes (>M5.5) occurring anywhere in the world are posted on the web within minutes of their occurrence. One such site is the National Earthquake Information Centre of the US Geological Survey. Strong-motion detectors are used to measure the local effects of major earthquakes, while the smaller tremors associated with volcanoes are monitored using more sensitive instruments, including broadband seismometers that detect the longer-period events characteristic of movement of fluids within the Earth's crust. Critical requirements for all networks are sufficient coverage and station density and real time data transmission capabilities.

> Mapping

Mapping, whether of bedrock geology, structure or surficial deposits and soils, is essential in trying to understand the geohazards. Field-based geological mapping not only provides observations that are impossible to achieve any other way, such as deformation fabrics that reveal the strain history in rocks, but it is also central to the development of knowledgeable and skilled geohazard scientists. It results in scientists that understand the phenomena in detail, who can successfully apply the other observations to its mitigation. Fieldwork is supported by airborne and EO data. Aerial photography analysed in stereo allows virtual fieldwork in the laboratory, which means that field visits can be targeted. Ground instability phenomena are best recognised this way. Airborne hyperspectral imagery from sensors like MIVIS, AVIRIS, HyMap and AHI, multi-spectral optical EO data and satellite radar imagery are all used alongside field work to identify surface mineralogy, soils, lithologies, topography, drainage networks, structures, and land-use. High spatial resolution, stereo satellite data increasingly substitute for aerial photography in identifying the characteristic geomorphologic features of geohazards and supporting both geological and soils mapping. The earthquake section of the CEOS DMSG report includes an extensive bibliography illustrating the use of aerial photography and EO data in mapping related to earthquake hazards. Mapping may be used both to establish a baseline and as a rapid reconnaissance after an event.

> Gas Emissions

Volcanic gas emission rates and plume composition are commonly measured using correlation spectrometers and infrared analysers (e.g. COSPEC, LI-COR) and, more rarely, the new open-path Fourier Transform Infrared spectrometers (OP-FTIR). These can be stationary or can be mounted on trucks or small aircraft. The necessary measurements require repeated passes beneath the plume under sunny conditions, preferably at different elevations. Such surveys are normally carried out on a monthly or annual basis unless the volcano is in a state of heightened activity. Direct sampling using specific geochemical sensors at critical sites is also used to monitor gases, in particular CO2 concentrations in soils at volcanoes that are known CO2 emitters. Soil gas monitoring along active faults has been attempted in the search for earthquake precursors; a key difficulty for this work is to know where to put the sensor. In addition, airborne hyperspectral sensors can be used to measure relative gas concentrations. SO2, the most characteristic volcanic gas, can be detected using multispectral UV and IR satellite sensors. The use of such sensors on meteorological satellites for monitoring SO2 plumes is reviewed in the CEOS DMSG report. Coarse spatial resolution and low sensitivity have in the past limited use of EO to detection of SO2 in volcanic plumes that reach the stratosphere. The wider suite of IR bands and higher resolution of the ASTER sensor on Terra allow better monitoring of tropospheric and more dilute SO2 plumes, hampered principally by a minimum

16-day revisit time and by clouds. The same sensors can also monitor stratospheric ash clouds.

> Temperature

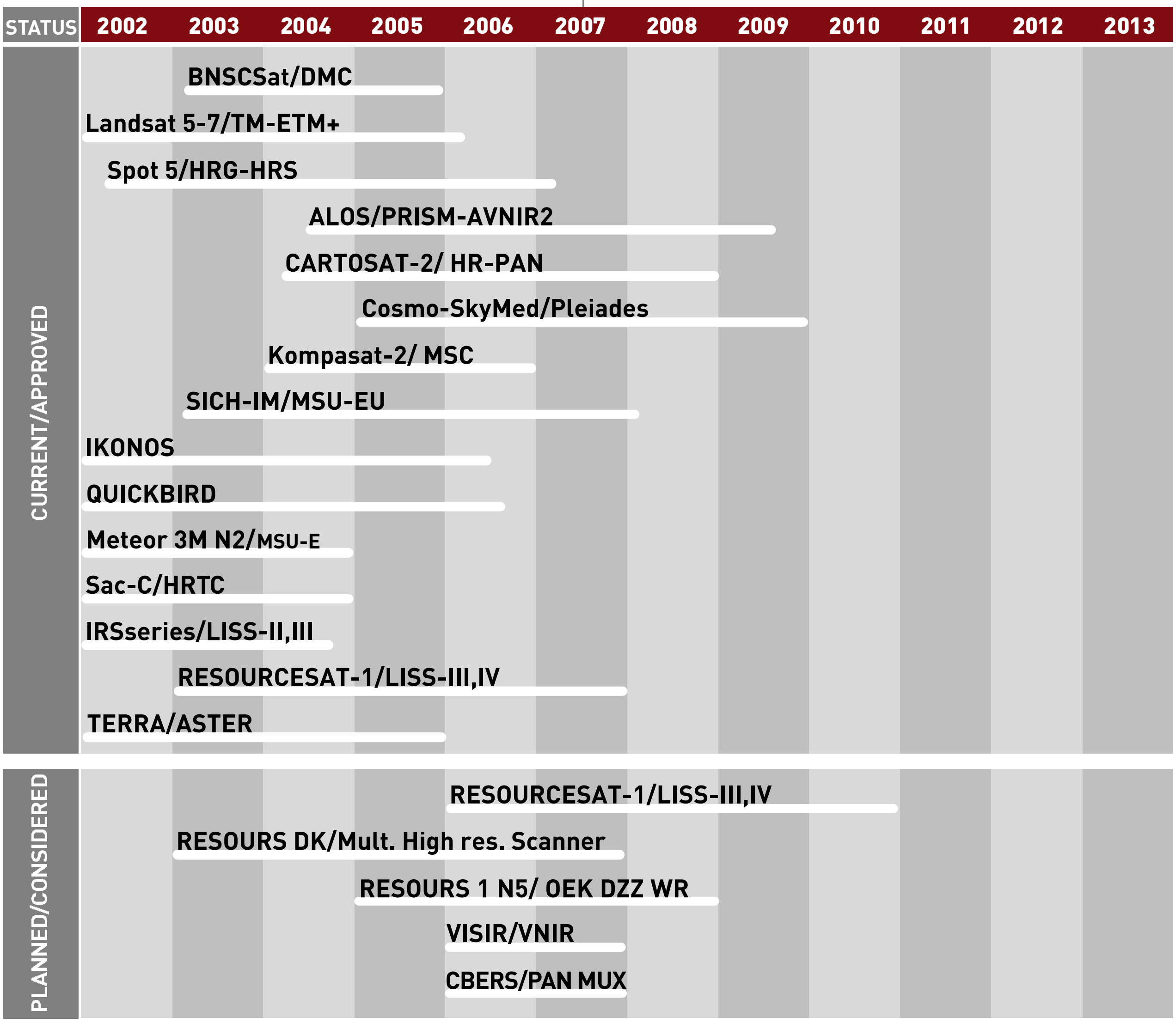
Ground-based methods include thermocouples, pyrometers, and other kind of standard temperature sensors. These approaches provide only periodic measurements at point localities, but are the principal means of evaluating thermal trends of lower-temperature sites such as hot springs, whether associated with volcanoes or with active faults. Fixed-position IR cameras or airborne cameras that measure emissivity and temperature provide detailed information on the structure of active lava domes, flow fields, and tube systems. Lava flow mapping and thermal surveys from hyperspectral sensors are also possible. Satellite remote sensing at various infrared wavelengths has been widely used for thermal monitoring of active volcanic areas. Its effective application depends on a good match between the resolution of the sensor and the size of the target. Available sensors with hight resolution include Landsat 7 and ASTER, though they offer only low observational frequency. For near real-time monitoring, high temporal resolution satellites in both polar and geostationary orbits are widely used. Data from NOAA's GOES satellites is routinely used for volcanic hotspot analysis, and the results posted on the web. NOAA's operational system of polar orbiting satellites provides observations of the entire globe at least every 6 hours at spatial resolutions of 1-5 kilometres, but the sensors saturate at hight temperatures. ESA has also conducted pilot projects (e.g. VOMIR) on volcano surveillance using the ATSR instrument series on board the polar orbiting ERS-1 and ERS-2 satellites, with the main objective to study thermal signals at a number of active volcanoes. Efforts to document thermal anomalies as possible precursors to earthquakes have drawn on the stream of AVHRR and ATSR data. New sensors like MODIS and SEVIRI, which have a wider range of IR bands, should allow monitoring of a wider range of temperatures. In fact the MODIS sensors on Terra and Aqua are already used to detect volcanic hotspots, with the results posted on the web. Unlike the GOES site, the MODIS hotspot site has global coverage.

> Physical Properties

Field and laboratory measurements, including geotechnical and geophysical techniques, furnish information on strain-state, hydromechanical and hydrogeological properties, and geological structure, especially within active landslides. In some cases, they help the detection of an early-activated zone and are usually included in any early warning systems. Geotechnical instruments include extensometers, inclinometers, crack meters, rupture and contact detectors, level-meters and pore-water pressure sensors. Ground-based geophysical techniques such as electric, electromagnetic, ground penetrating radars, protonic resonance magnetics and active seismic reflection and refraction techniques are used in the detection and/or characterization of some relevant parameters involved in ground stability assessment. They permit the non-invasive investigation of subsurface conditions. These measurements are then used to directly or indirectly deduce permeability, water content, porosity, chemical constituents, stratigraphy, geologic structure, and other properties. The level of detail of the information to be derived by such instrumentation is dictated by the size of the phenomenon and by the purpose of the analysis.

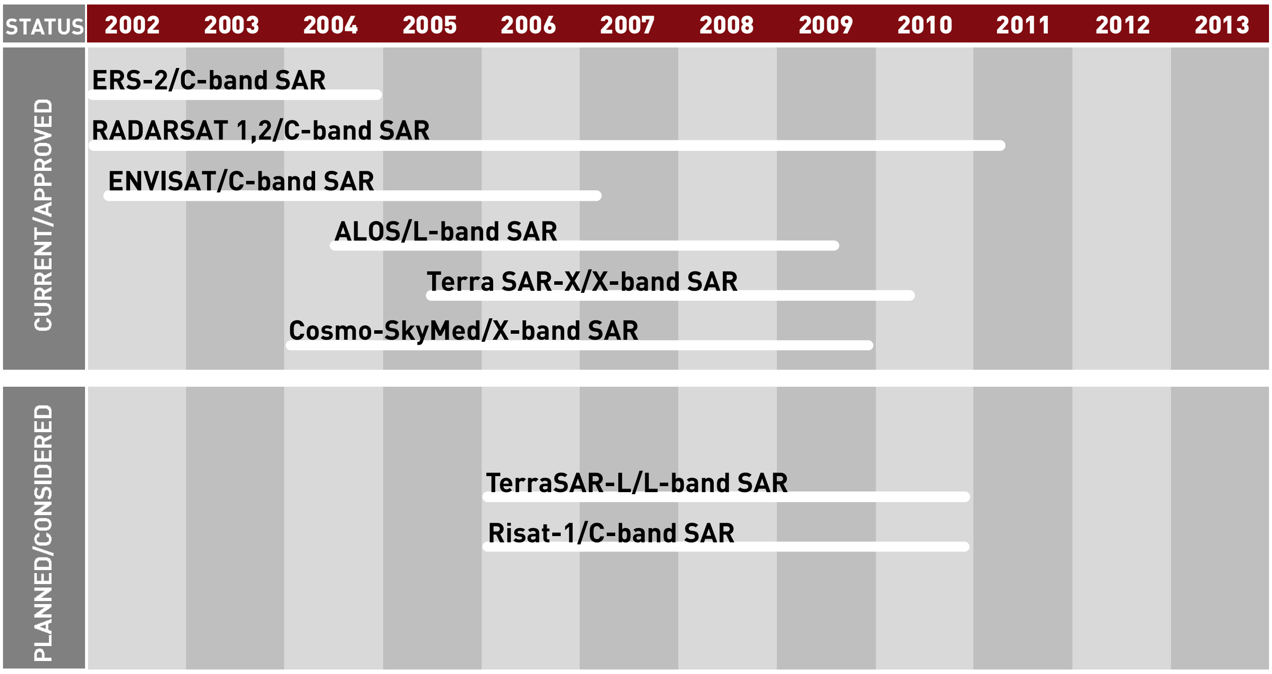
A number of other observations are occasionally measured for all three hazards but are not yet fully established and therefore do not form a core part of the geohazards IGOS. Nevertheless they have been shown to be of interest under specific circumstances and they should be considered further as part of the underpinning research agenda. They include the in-situ measurement of electric or electromagnetic properties, which are affected by the migration of fluids and gases in the subsurface. Such migrations occur for all three hazards but the related electro-magnetic effects are not yet understood well enough to demonstrate their value to operational monitoring. For example, in the case of volcanoes the signature of the geothermal system that exists under any active volcano dominates their response and so their relationship to the magma system itself is uncertain. Their integrated study alongside the more established observations may serve to reduce ambiguity in their interpretation. Over time this is expected to sharpen scientists' ability to recognise precursor phenomena for all three geohazards.

New tomographic techniques for geophysical data inversion (resistivity imaging, reflection and refraction seismics) can be applied to the mapping of active faults, to define the geometry of complex tectonic structures and to characterise shallow geological environments generating local seismic amplification phenomena. Total Electron Content maps, as derived by dense GPS networks, are another observation yet to be integrated with established techniques to investigate the possible

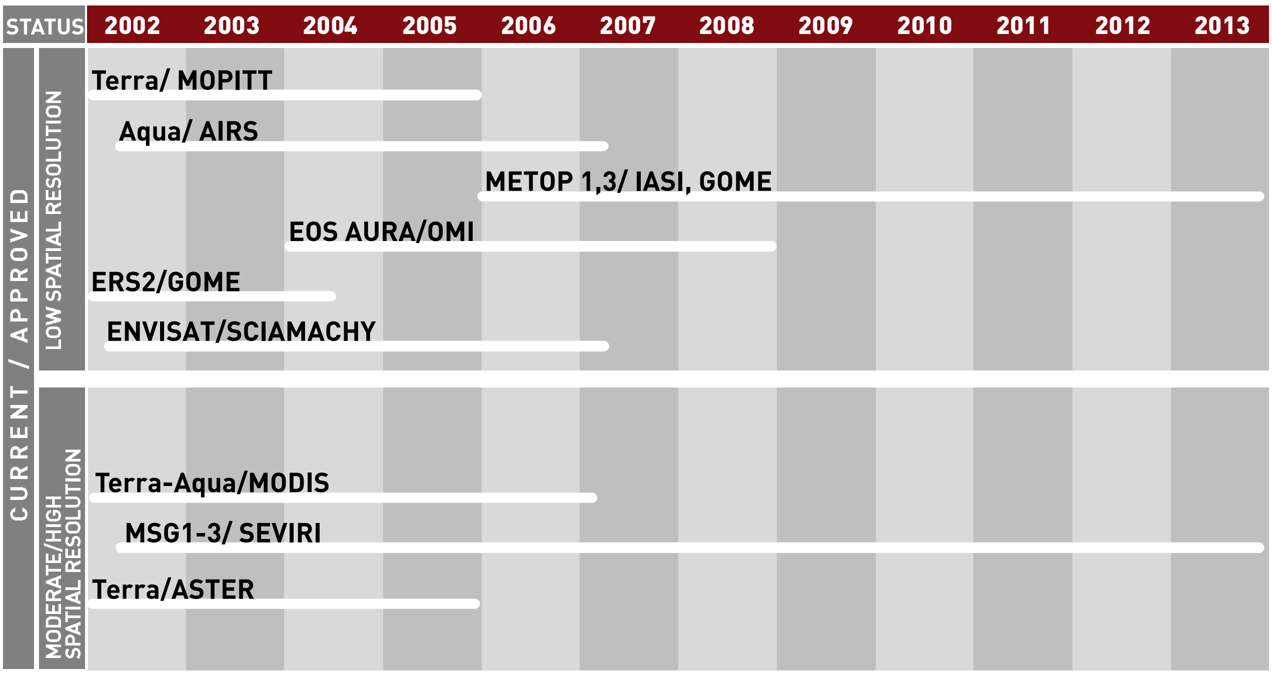


High resolution stereo and panchromatic sensors to be used for topographic and geological mapping, map generation and updating, land cover maps, inventory maps....

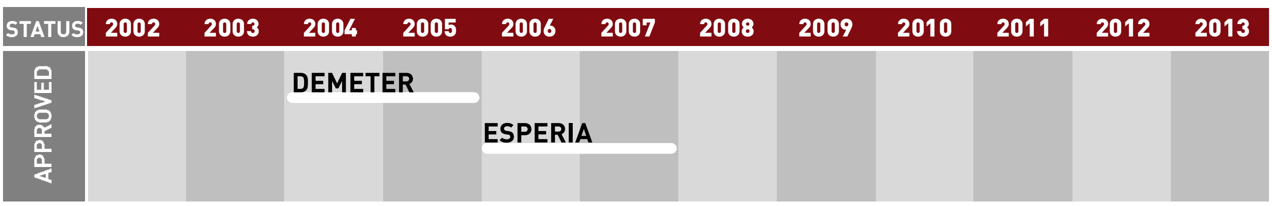
relationship of gravity waves to earthquakes. The proposed DEMETER mission will advance understanding of the possible relationship between ionospheric perturbations and earthquakes. The TOPEX/POSEIDON mission may result in a similar advance for total electron content mapping. Ground-based SAR interferometers may be a solution for monitoring landslides, because of their high temporal frequency. The main advantages are continuous monitoring, optimal illumination geometry, flexibility and the possibility to remotely monitor landslides up to a distance of about a kilometre, the latter being especially important when landslide sites are not easily accessible with traditional instruments. These systems can also offer two dimensional images, rather than sparse point-like GPS measurements, and offer cost-effective solutions for specific sites, where the system can be properly installed and long-term monitoring properly established.



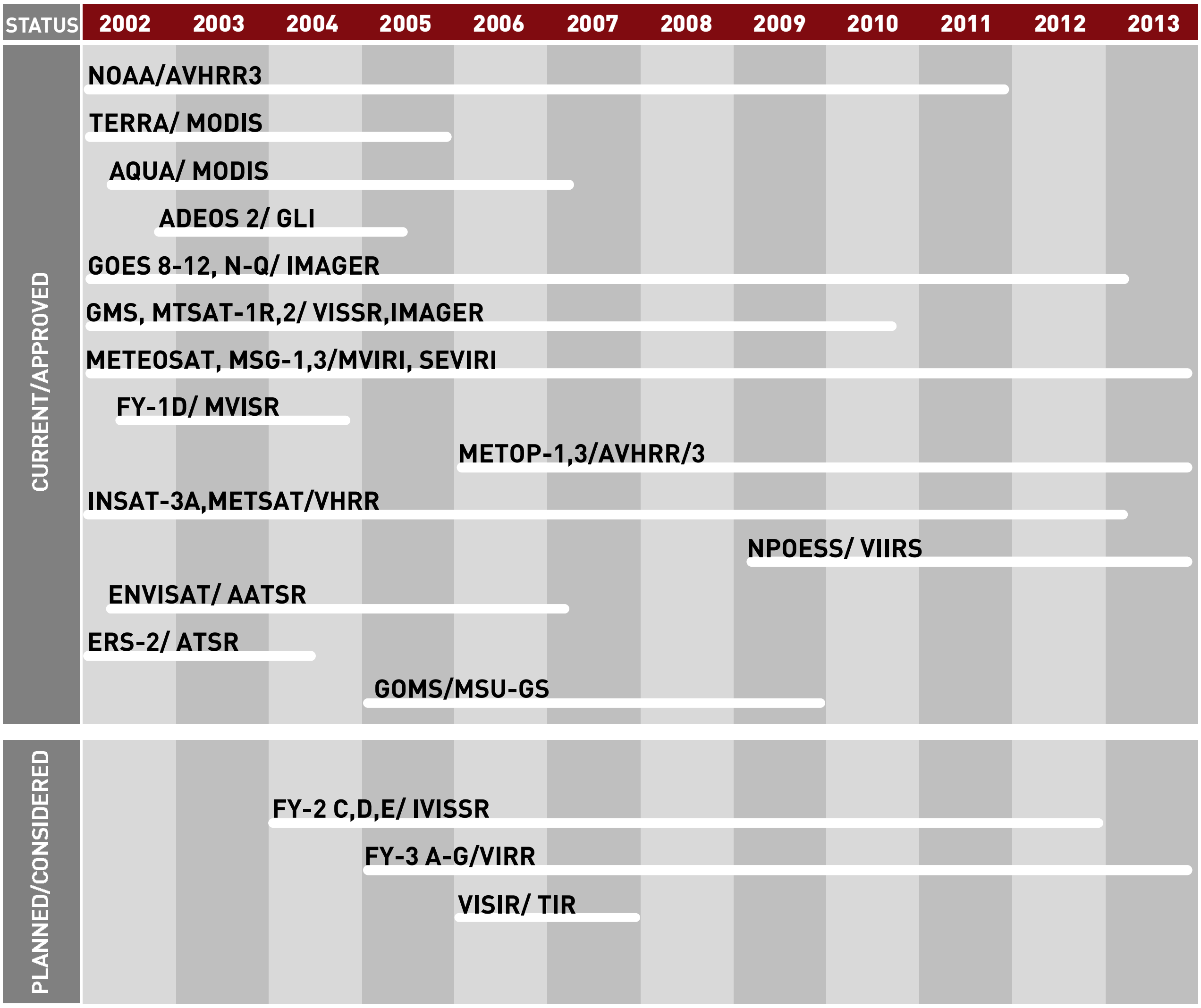
The key current and future satellite missions and sensors for ground displacements observations and topographic mapping by InSAR techniques.



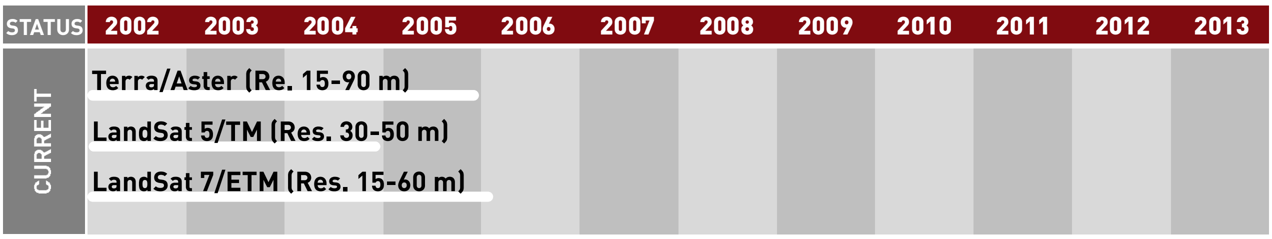
Major EO missions for Volcanic gases (mainly SO2) observation.



Future missions for ionosphere observations



Current and planned EO Missions for thermal monitoring at moderate spatial resolution (from hundreds to thousands of meters) and high observational frequency (from tens of minutes to few days).

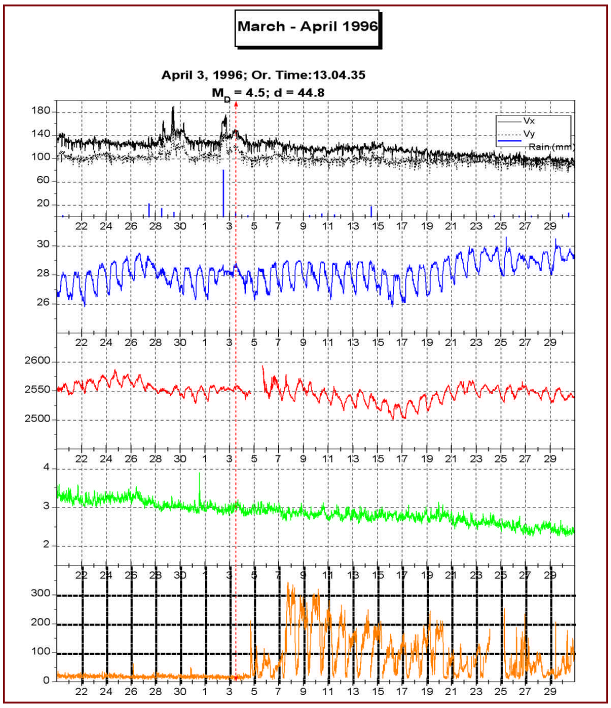


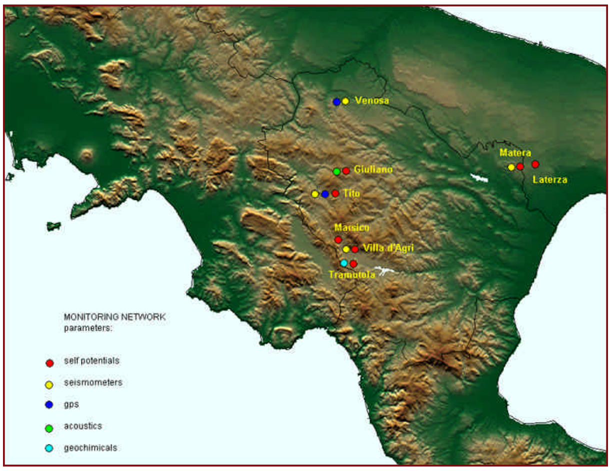
Current and planned EO Missions for thermal monitoring at high spatial resolution (from tens to hundreds of meters).

The previous chapter demonstrated that four main observational requirements are central to this strategy: topography, deformation, seismicity and geoscience mapping. But geohazard mitigation requires far more than simply facilitating the correct observations. There must also be an infrastructure in place to turn them into useful information and to get this information to the people who need it. This chapter describes the management of the data resulting from the observations and its integration into products via modelling and assimilation. It also discusses the capacity building and education that are required in order to address the long-term strategic objective of integrating the global geohazards community more effectively

DATA MANAGEMENT

Integration is needed on many levels, from the observations being made to the communities making them. The first set of integration issues concern the establishment and maintenance of properly collected and evaluated observational data for the geohazards. The observations from the various observation systems need to be added to databases that ensure long-term preservation and curation. These archives or databases need to be complete in terms of global geographic coverage and the range of appropriate data types, contain validated, consistent, geographically registered data and be archived securely. Their very existence encourages long-term continuity of observations, supporting ongoing monitoring and research whilst at the same time ensuring that historic data exist when they are required during a specific event. Both update and access must be rapid and efficient, even when operating in remote locations, and should be supported by appropriate metadata. Pricing, IPR and copyright apply to any data but policies should not hinder access by those who need multiple repeat acquisitions of EO data in order to solve geohazard problems. Data formats and database designs should foster data sharing and interoperability. Many essential databases and archives already exist for selected geohazards data. Examples include IRIS, the global archive for seismic records, supported by the National Science Foundation, with data freely available to participating institutions and investigators. UNAVCO plays a similar role for the GPS data user community. The EROS Data Centre of the USGS archives all Landsat and ASTER data, as well as other airborne and EO data streams, and similar archives exist at the various space agencies. The Smithsonian Global Volcanism Project and its monthly bulletin are the archive of record for volcanic activity, worldwide. However, comparably broad archives with full descriptions of events are largely lacking for earthquakes, and especially for landslides and ground instability hazards.





Multiparameric monitoring network installed in a seismic active area of Southern Apennine chain. The stations are equipped with sensors to detect seismometric, geodetic, geochemical and electromagnetic parameters. Contemporary plots of Self-potential, Water spring temperature, CO2 concentration, Water electrical conductivity, and Radon emission, during two months before and after an earthquake occurred in the area on April 3rd 1996 (by courtesy of IMAA-CNR).

DATA INTEGRATION AND MODELLING

The existence of such databases facilitates the development of software for modelling or for integration of different streams of data. Scientists in monitoring and observation services access the databases to feed data into models describing the behaviour of the various geohazards. A research agenda must exist that results in increased knowledge of geohazards and continuing improvements to these models. As the science develops, more complex models will require a large number of in-situ, airborne and EO data sources to fully describe a given situation and provide reasonable advice on what can be expected to happen under various scenarios. Existing examples of software for data integration include VALVE (Cervelli and others, 2002) and most GIS systems. Process modelling software includes LAHARZ, which models lahar development and run-out (Schilling, 1998). A variety of integrated data management systems have been proposed for volcano-related data, including Geowarn and EMEWS. An example of a second-generation, integrated database for historic examples of volcanic unrest is the proposed WOVOdat project. Here the input is to be the integrated, evaluated results of well-characterized volcanic eruptions or episodes of volcanic unrest that did not lead to eruptions. The goal of this project is to facilitate the sharing of experience among the volcano observatories of the world, to help compensate for the relative infrequency of eruptions at any one volcano.

CAPACITY BUILDING

Another critical need for global mitigation of the geohazards is capacity building in parts of the world where the scientific and monitoring infrastructure is weaker. An example of an existing programme that has capacity building as its purpose is the Volcano Disaster Assistance Program (VDAP) of the US Geological Survey, formed in 1985 in response to the disaster at Nevado del Ruiz. At the invitation of the host country, VDAP personnel bring and install seismic, deformation and gas monitoring equipment, train local personnel in its use and maintenance, and offer their experience in interpreting volcanic unrest to local scientists. A related program is the Centre for the Study of Active Volcanoes (CSAV), a cooperative project between the University of Hawaii and the Volcano Hazards Program of the USGS. Based in Hilo, this program provides small groups of carefully selected scientists from developing countries a 6-week course of intense training in volcano monitoring techniques, with Kilauea volcano as the laboratory. Over 70 scientists and technicians from developing countries have been trained at CSAV since 1989.

aking best use, globally, of the existing infrastructure requires an integrated geohazards community, both between the three geohazards and between the various stakeholders and users. The strong commonality emphasised in this strategy between volcanic, earthquake and ground instability hazards needs to be exploited by developing shared experience and shared solutions. Users and scientists in both the public and private sectors must communicate in order to understand both what is required and what is possible, so that appropriate information products can be developed. Examples of existing organizations include IAVCEI for the volcanology research community and WOVO, for the volcano observatories around the world. Equivalent organizations for earthquake research include IASPEI. The EO provider community has organized itself into CEOS, and has sponsored the Disaster Management Support Project. The CEOS DMSG report includes chapters with extensive discussion and recommendations for each of the three geohazards in this IGOS. However it is conspicuous that there is at present no one community and no one organization that encompasses all the geohazards and is therefore well placed to take these recommendations forward.

This lack of a united community has a negative effect on the recognition of the needs and impact of the geohazards, and on attempts to seek sponsorship and funding for large-scale projects critical to the geohazards. This report, following on the heels of the CEOS DMSG report mentioned above, constitutes a concerted effort to reach the policy makers, legislators and funding agencies, who alone can make large decisions. Focused, coherent funding mechanisms are needed to underpin initiatives such as the International Strategy for Disaster Reduction, as well as this geohazards IGOS, especially as we seek to move beyond science in the developed countries into the rest of the world via education and training, knowledge and technology transfer and general capacity building in appropriate institutions and industries. One of the most effective steps that can be taken is to spread best practice: for example, ways should be found to apply new techniques developed at a few well-monitored volcanoes to the majority of dangerous volcanoes around the world. Similar steps can be taken for each hazard, using strong case histories to facilitate this knowledge transfer process. Such case histories can form part of dedicated geohazards curricula and courses to grow the community in the future ■

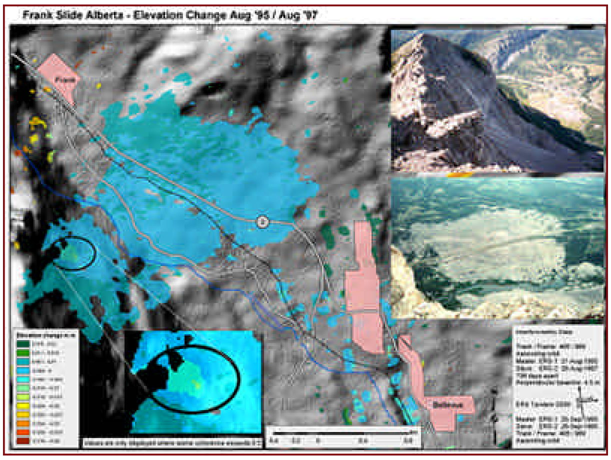
Previous chapters have described the needs of beneficiaries, users and stakeholders for information and hence observations. The observation systems that can provide for these needs have been examined and various data management, integration and modelling issues have been explored. The requirement for a geohazards IGOS to build the global geohazards community has also been defined. This chapter analyses the current provision of observations, key systems, community integration and scientific knowledge in order to identify the gaps that the geohazards IGOS must fill over the coming decade. It also identifies a science research agenda that is required to underpin delivery of the strategy.

GAPS IN OBSERVATIONS AND KEY SYSTEMS

Global provision of topographic data at sufficiently high spatial resolution is currently inadequate. DEMs can be used to extract geomorphologic information when mapping geohazards, as an input layer for interferometric processing and they are the source of both primary and derived information in susceptibility and hazard mapping or modelling. There are large parts of the globe for which the scale of DEM required is not available. The provision of a global dataset is too great a task for the use of ground-based or airborne techniques to be appropriate. Satellite-derived DEMs cover large areas with a far lower cost than aerial surveys. Furthermore, archived data already exist over most parts of the world that have not yet been mapped. The main limitations are the product's resolution, availability and cost. Interferometric DEMs derived from ERS, SRTM or Radarsat in the best case might have a spatial resolution of tens of meters. Techniques based on photogrammetry can be applied to imagery with higher ground resolution (such as ASTER, Spot5, Ikonos or Quickbird) and could provide vertical resolutions on the order of 5 m or less. The EO data exist and the challenge is to turn them into a useful product and make it available to the geohazards community.

The second requirement is for observations enabling the measurement and monitoring of the deformations induced by the different geohazards. The techniques used to measure deformations are basically the same used for topographic mapping, employed over an extended time period to measure topographic change. Ground measurements involve a wider range of instruments, focusing on the measurement of movements along vertical or horizontal axis or the quantification of tilting. In the case of GPS, measurements along the vertical axis have a lower accuracy than along the horizontal axis, therefore prominently vertical ground motion such as subsidence cannot be analysed with high accuracy. Temporal sampling of the ground-derived data can be very high, but data must be acquired through dedicated campaigns and no previous (archive) information is generally available. Such data acquisitions are therefore project specific and the challenges lie in databasing and accessibility.

Satellite radar interferometry provides the capability to map past and ongoing deformations, day or night, in all weather and over wide areas in the absence of such ground networks. The CEOS DMSG Report concluded that building up long time-series of Radar images over sensitive locations would enable exploitation of multi-interferometric techniques. The main limitations relate to the continuity and frequency of current INSAR observations,

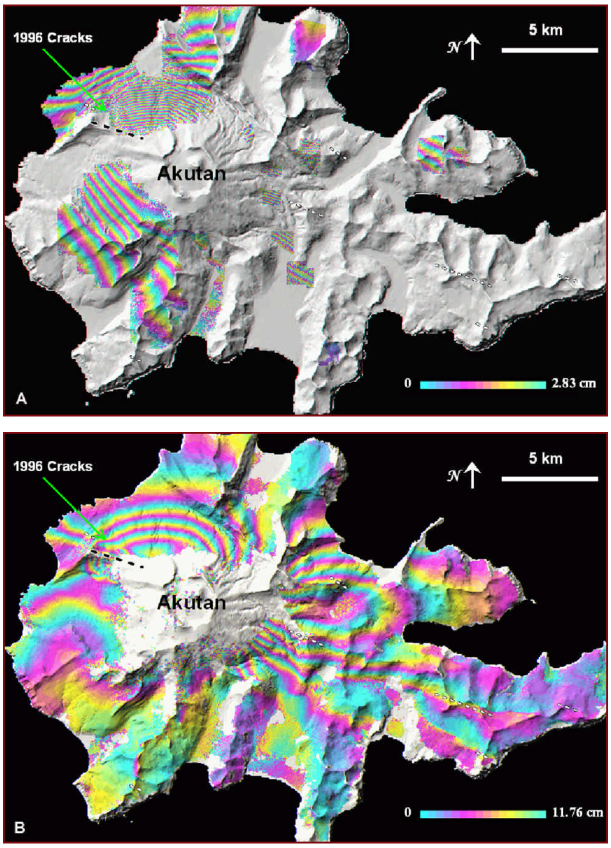


Differential InSAR of Frank Slide, Alberta, shows 3 cm motion prior to 6000 tons rockfall, indicating that this rock slide is still active. InSAR will be used to supplement in-situ tools and to monitor regional motion of the active slide area. The right/left look direction, high resolution and variable viewing geometry of RADARSAT -2 will be used to monitor most the active slides. (image Courtesy of CCRS)

restriction of existing measurements to the line of site and the limited capability of existing systems to map deformations over wide enough variations in land cover. Thus far continuity has been limited by the life of particular sensors; although it can be done, interferometry between ERS, Envisat and Radarsat is much harder to achieve than within just one mission. Sufficient frequency of observation has only been achieved during the ERS Tandem Mission, when it was shown to be possible to monitor landslides using data acquired on a 1-day interval. L-band SAR (such as the planned PalSAR and TerraSAR missions) has been shown to work over a wider variety of vegetated land surfaces than C-band, albeit with a detection threshold of centimetres rather than millimetres, by studies based on the previous JERS mission such that over Akutan Volcano in the Aleutians. The requirement is for continuity of observation, both at C-band via continuation of existing missions and via a new L-band SAR mission. This should have the lifespan of the Landsat programme, be optimised for this application, have sufficient look directions to resolve motion in three dimensions and be tasked specifically with interferometry in mind in order to provide sufficient frequency of observation. Generic missions have been used to great effect in research mode but they involve compromises in spatial, spectral and temporal resolution that limit the utility of these observations for operational geohazard mitigation in general and long-term monitoring in particular.

Thermal data have application to volcanic and earthquake hazards. Observation systems operated by NOAA and METEOSAT have been providing frequent data on temperature at a regional scale for more than twenty years. This is now supplemented by less frequent but more detailed data from satellites such as ASTER. So, current satellite-based observations of temperature are either frequent but at too low a spatial resolution or at an adequate spatial resolution but too infrequent to have a significant impact on geohazard monitoring. It is possible to envisage a coordinated system exploiting the complementary attributes of all these existing systems, combined with increased acquisition of night time data and integration with ground-based observations that would allow improved time series temperature data to be built up over hazardous areas. This could go some way towards closing the gap. Ultimately, an improved thermal mission with an increased frequency of higher spatial resolution observation should be developed.

There are fundamental inadequacies in baseline mapping that the geohazards community needs to put right. The first concerns hazard inventories. In contrast to volcanoes and earthquakes, the extent of the affected area is not yet known in detail for ground instability. Landslide inventories and subsidence histories must be constructed for all affected regions. The second is geological and soils maps, which are at an inadequate scale or simply do not exist for many parts of the globe. Filling these gaps in observations is more to do with securing the funding by international agencies of appropriate mapping projects and the subsequent databasing of the resulting products. It also requires supporting observations from existing optical and radar satellites, however, but the issues concern access rather than observation and are dealt with below.



A: interferogram of Akutan Volcano in the Aleutians, made from C-band ERS imagery (Lu and others, JGR, 2000) is only locally coherent (rainbow areas). B: interferogram made from L-band JERS data (Lu and others, GRL, 2003) has fewer fringes, but achieves coherence over almost the entire surface of the island, allowing us to see the entire deformation pattern. To date, the JERS SAR mission has not been followed up with a new L-band instrument and so such observations are not currently possible. (image Courtesy of USGS)

Several types of observation that have been shown to be useful at specific sites would be difficult to extend globally. It would also be a challenge to ensure long-term continuity of observations at remote sites. Hazards such as volcanic eruptions, that last for decades or more, pose maintenance burdens on monitoring networks and data management systems, as well as on the population and environment. It is therefore necessary to define which parameters, of the dozens of parameters that can be monitored, are absolutely critical to monitor continuously and how best to go about that. For example, in volcanology the key issue is the provision of adequate seismic networks at all hazardous volcanoes sited in populated areas. Experience at well-monitored sites has shown that six seismometers provide a minimally adequate network for one volcano. The geohazards IGOS should result in the definition of minimum observation plan for all the geohazards, with observational requirements being added to the

WMO database. These can be different for the monitoring phase and during an ongoing crisis. Observation plans should allow for the rapid densification of the networks and the addition of extra observations once a hazard becomes active.

GAPS IN DATA MANAGEMENT

The target here is to create "strategic datasets" for particular geohazards, backed up by well-documented case studies. The existence of such datasets will facilitate the production of ancillary data for hazard mapping, guide ongoing systematic acquisitions over hazard-prone areas and drive new, targeted acquisitions during a crisis.

At a basic level databases exist for most types of Earth Observations, often as part of a processing and archive facility, and for many ground-based measurements, as part of particular organisations' data management strategies. The gaps that exist relate to the visibility and fitness for purpose of these data stores. The requirement is for much more than storage within a single organisation. Databases are needed with a high visibility within the geohazards community that facilitate the transfer of data, information and knowledge between different types of users in different countries. Interoperability of databases is crucial, as geohazards require multidisciplinary research and the heterogeneous nature of existing databases can be an obstacle to the progress of our understanding of failure mechanisms. This leads to the need for the creation and population of international geohazards databases. A good example of what is required is provided by the evolving World Organisation of Volcano Observatories database. Similar initiatives are needed for all the geohazards. Such databases should contain both baseline data and the outputs of monitoring activities, including relevant ground-based data from geoscience organisations and also data from existing satellite archives. The data in them should be calibrated, validated, put into a standard format and quality assured prior to databasing.

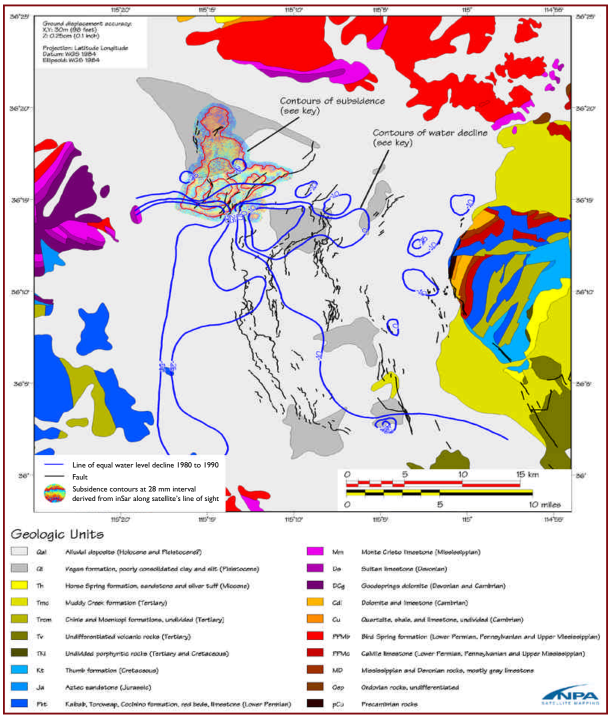
This geohazards IGOS should develop operational, and perhaps even automated, arrangements that will make the transfer of data to information to products happen more efficiently. Mechanisms are needed to facilitate the rapid and smooth transfer of data from the space agencies to the scientists monitoring geohazards and of information from the scientists to the users. As soon as an image is acquired over sensitive areas, the data provider should send an automatic notification to a list of subscribers interested in imagery over specific geographic locations. Pricing strategies are not currently designed to facilitate repeat data purchases where they form part of a strategic monitoring programme with long-term continuity and they should be reconsidered. Some INSAR studies of deformation require the purchase of fifty or more images over a ten-year period. In a more advanced phase, data could be automatically processed at the scientist's premises and, as soon as useful information on a hazard existed, the processed image products could be sent to the local users. Technological developments like extranet solutions and the emerging, advanced computing GRID network should be used to manage, access, exploit and distribute the large amounts of data and information products required by geohazard mitigation. Provided that adequate models, appropriate software tools and sufficient observations exist, the end users could even activate this process, rather than the scientists.

GAPS IN INTEGRATION AND MODELLING

Improved databases, complemented by shared experience and improved analysis and modelling tools like neural networks, fuzzy logic, statistical, stochastic and geostatistical methods, will open new possibilities for developing geohazards analysis.

Integration of data acquired at different resolution, with different accuracy and geometric characteristics from different observation systems needs a major effort from the scientific community. For example, the techniques needed to monitor deformation include both satellite-supported INSAR and ground-based monitoring, with GPS monitoring combining elements of both. The methods are complementary: ground-based monitoring can provide a record of deformation at a specific point on the ground that is continuous in time, while INSAR gives us periodic measurements of the areal distribution of deformation over wide areas. Both are needed in a monitoring scenario and they can also be used to validate the observed deformation, increasing confidence in both individual results. Surprisingly few studies make use of both approaches as yet. The integration of data acquired at different spatial, spectral and temporal resolution, with different accuracy and varying geometric characteristics needs a major effort from the scientific community. To date the integrated use of ground and satellite data is generally limited to inter-comparisons and data calibration.

Prediction of future events requires models and numerical simulation tools based on well-understood Earth system processes. There is a proliferation of different models with widely differing assumptions, depending



Geology and faults of the Las Vegas Valley area in Nevada, overlaid with the 1980-1990 water level decline contours and InSAR-derived subsidence field. Sources: Digital geology: Nevada Bureau of Mines and Geology, County Digital Geologic Mapping Project, Final Report, 1:250,000 scale maps for Clark County, Open File Report 91-1, 1996; Digital contours of water level decline (1980-1990) and 1:24,000 scale faults: Subsidence in Las Vegas Valley 1980-91- Final Project Report, NBMG, Open File Report OF 93-4, 1992. Copyright Nevada Bureau of Mines and Geology, 1991; Deformation: ERS SAR data pair dated April 93 and April 96 interferometrically processed. Copyright NPA 1999, ESA 1993/96. (image Courtesy of NPA)

on the scales of investigations. This is of major importance for hazard mapping and monitoring of events ranging from local to regional distributions. Models vary from simplified to complex. The former are approximate, but they necessitate fewer input parameters and may be applied to large zones. The latter are sometimes indispensable for evaluation of the stability of a specific, dangerous ground instability hazard but are data hungry. In both cases, it is necessary to establish their capability, accuracy, and sensitivity with respect to the needed effort for gathering model inputs. Numerical simulations are still rare, especially for example in ground instability studies, due to the difficulty of obtaining the required input parameters and the heavy 3D computations involved. The development of reliable physical models requires a better understanding of physical processes, thresholds in physical properties and triggering mechanisms. Field observations and laboratory experiments should be carried out to advance this.

This geohazards IGOS can also contribute to the development and documentation of standard data processing software and protocols and standard information products. Some standard products exist but only in certain countries and for certain hazards. The Geohazards IGOS should extend this to all hazards and ensure that such standard products become established in the wider geohazards community. An example of a standard product that is already produced for certain volcanic hazards is the Mt Rainer hazard map. Similarly, standard visualisation tools are needed that can be used by scientists and users alike to rapidly analyse new information products as they are produced, whether working in the laboratory, at an observatory or in the field. Finally, work should continue on the improvement of Earth system process models via the research agenda proposed below.

BUILDING THE GEOHAZARDS COMMUNITY

Currently there is no global coordination mechanism to implement the geohazards IGOS. One result of this is relatively poor integration within the geohazards community in comparison to, for example, the Oceanography or Meteorology communities. Communication needs to be increased between all the key players. This lack of integration hinders many other desirable actions. Users do not consistently define information products through dialogue with monitoring and advisory agencies. Scientists do not consistently define the required observations that the observing systems should make and do not work in an integrated fashion across their disciplines, technologies, or application areas often enough. Appropriate technologies and methods for developing world applications are lacking. The best students are not attracted to study and consider careers in geohazards, with most expertise developing during general geoscience careers and coming into the geohazards field by serendipity in mid-career.

Funding is also dispersed and predominantly governed by the priorities of individual organisations, regions or nations. An example of this is that the International Strategy for Disaster Reduction has no dedicated funding, unlike equivalent initiatives in other application areas. Geohazards sometimes have limited visibility in wider decision making processes; for example, the impact on hazard monitoring of the high price of bandwidth for satellite data links, caused by telecommunications market, is not being addressed at present because the geohazards community does not have a voice in that decision making process. The first step must be to create a coordinating mechanism. This should then be used to encourage improved communication throughout the geohazards community, foster the transfer of knowledge and information from the developed to the developing world, and develop curricula to stimulate study courses dedicated to geohazards. Development of such a community will also have spin off benefits in crisis response, by enabling the rapid gathering of expertise during a crisis.

SCIENCE RESEARCH AGENDA

Underpinning the solution of the social and economic issues created by geohazards is a pressing need to understand and describe the associated scientific issues better. Models are required which characterise Earth system processes associated with hazards. The models being developed demand the measurement of a wider range of parameters than is currently standard and new observing technologies will ultimately be needed to measure them. The ultimate goal is for advances in knowledge to feed through into operational scenarios in monitoring and advisory agencies and so increase our ability to mitigate hazards and bring closer the ultimate requirement for accurate forecasts and predictions.

New techniques and data on emerging parameters may already exist and have been applied with varying degrees of success at one site or another. What is often missing is the wider testing of such approaches at a range of well-characterised sites, their consequent validation and refinement and their development, if warranted by results, as mainstream tools that can be used alongside others in observatories. The IGOS Geohazards Theme Team is aware of a number of such areas that are ripe for development and so it proposes a scientific research agenda to take care of this issue. This agenda will be developed on the same schedule as the more operational steps set out above. It has four inter-linked aspects that characterise all of the following examples:

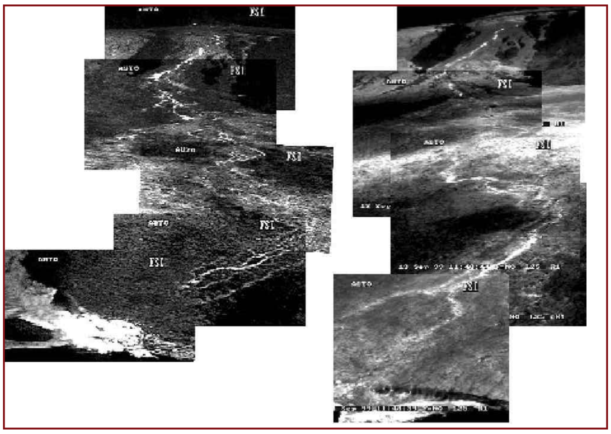
- Improvements in geohazards knowledge and understanding;
- Investigation of new observational tools that offer promise;
- Data continuity in the provision of less well-established observations; and
- Integration of emerging research results into mainstream observatories.

Deformation is of paramount importance for studies of geohazards. Considering earthquakes, enhanced understanding of behaviour will result from better linking of the pre-, co- and post-seismic motions to earthquake processes. Observations of pre-seismic strain and tilt are reported in literature. Relative displacements along faults are currently measured by updated GPS campaigns, but for pre- and post-event deformation analysis, continuous measurements are required. There have been only a few cases of direct observation of pre-event displacement. Water level fluctuations in wells and sea level change can be considered as an indirect sign of motion. Preliminary analysis of pre-seismic displacement shows it to have magnitudes on the order of few centimetres, over times ranging from days to months. Co-seismic motion describes the mechanism of the earthquake and provides information about the energy dissipated and the way such energy has been distributed and perceived on the surface. Post seismic motion gives information about crust's rheology and may result in essential information for the "calibration" of models. A better knowledge of ongoing deformations from interferometry and GPS measurements across all the main active faults, coupled with other geodetic, hydrologic and geophysical data will help scientists to understand the way the crust deforms in interseismic periods. The cumulative effect of this strain is to produce a topography that, with careful study, could provide significant inputs to long-term hazard assessment. Other questions concern the focal mechanisms of the earthquakes and how ruptures evolve kinematically and dynamically.

An understanding of patterns of motion before, during and after events is also central to enhancing our understanding of ground instability processes. The size of the area affected may vary between a few tens of square meters to several square kilometres. The speed of the motion may range from millimetres per year to metres per second. Rates of motion often change in space and time. Motion direction depends on the type of phenomenon: subsidence has a strong vertical component, whereas landslides usually have a horizontal component as well. Of critical importance are the processes that trigger that motion, whether natural or anthropogenic, including rainfall events, earthquakes and human modification of land-cover and land-use. Field instrumentation can be deployed to monitor, at defined locations, several parameters of interest associated with the ongoing deformations: seismometers, extensometers, inclinometers, crack meters, rupture and contact detectors, level meters and pore-water pressure sensors are frequently used in practice. Significant effort is still required to characterise and understand this wide range of ground movements and related triggering phenomena better in order to improve mitigation advice and bring accurate forecasting closer.

Seismic data are vital in the case of volcanoes. The recent development and deployment of broad-band seismometers, capable of recording long-period earthquakes (with individual events lasting 10-100 seconds) has shown that scientists still have much to learn about the range of seismic signals caused by the movement of magma, hydrothermal fluids and gas within volcanoes. At present, evaluation of these data is in the sphere of research but it will improve our models of how volcanoes work significantly. Once this has been achieved, strategies for monitoring will need to be changed accordingly. If certain types of events are shown to be reliable indicators of magma movement, and hence of an impending eruption, the geohazards community will need to consider how best to support widespread installation of this new type of instrument. This example demonstrates the strong reinforcing link between new science and new observations.

Thermal information is generally used by volcanologists to qualitatively forecast eruptions, due to the large range of temperatures that can be usefully monitored in connection with volcanic unrest (ranging from 30-40°C to 1200°C), to the reduced size of diagnostic heat sources, and to the mobility of these features. Scientists have sought to use existing IR satellite sensors to look at thermal signals from volcanoes. The high temporal resolution of imagery from meteorological satellites has led to its being used to monitor for hot spots at volcanoes. Harris and others (2000), based at the University of Hawaii, post processed imagery from GOES-8 and -10 on the web. Such data have proven useful as detectors of volcanic activity, of the varying intensity of an eruption, or of a shift in location of the activity. They are also effective at dispelling erroneous reports of eruptions at remote volcanoes. But the spatial resolution is too low to be of major impact on operations at observatories. A promising new technique, which allows both high spatial and temporal resolution, is the use of an in-situ equivalent. Portable digital infrared cameras can be used to obtain



Infrared video images showing details of the flow field and lava tube system at Kilauea Volcano, Hawaii (Kauahikaua and others, 2003).

highly detailed thermal images of active lava flow fields and domes at whatever time interval scientists require. The cost of supplying digital IR cameras to all of the volcano observatories of the world would be a small fraction of the cost of building even one satellite that could achieve the same resolution from outer space.

Also in the research field for thermal measurements, observations of surface and near surface temperature changes prior to earthquakes have been reported for a number of earthquake events, accompanied by changes in soil moisture and gas content and perturbation of atmospheric parameters. Much of the work to date relies on local, historic data and reports, is under active debate and so no consensus has yet emerged. This is a classic example of an earth system process that needs to be investigated and understood by gathering integrated observations at a global scale over an extended time period. The challenge is to establish what relationships exist between thermal anomalies and earthquakes and to measure them at sufficient sites and on enough occasions that this approach can be validated and integrated with the established suite of earthquake monitoring technologies. This requires the collection of long time-series data, especially nighttime thermal data collection, and the application of all-weather microwave methods for surface temperature retrieving. Research should aim towards the development of unified algorithms for surface temperature calculations and the development of models explaining the thermal behaviour in terms of earthquake processes. The best approach will be to integrate satellite derived temperature and deformation data with in-situ thermal, chemical, hydrogeological, meteorological observations and established monitoring approaches.

Gases are a third area offering promise. The principal gases emitted by volcanoes are H_2O, SO_2 and CO_2 and increased emission of steam, SO_2 and/or CO_2 are reliable indicators of an impending eruption. Of these, SO_2 is the most characteristic of volcanoes and volcanic eruptions and the easiest to detect: the human nose is very sensitive to SO_2 and other sulphur gases. Also, the SO_2 molecule and sulphate radical are readily detected using ground-based instrumentation to give point measurements at specific sites. The principal scientific challenge has been the difficulty of mapping low-altitude SO_2 and aerosol plumes over wider areas, for which satellite based measurements are required. The presence of the appropriate bands (in the 8-8.5 micron range) on the high spatial resolution ASTER sensor, integrated with more frequent observations from lower spatial resolution sensors such as MODIS (daily) and SEVIRI (every 15 minutes) offers the best opportunity yet to map such plumes from space and future hyperspectral satellites will improve on this. The geohazards IGOS will encourage scientific exploitation of existing and future satellite and ground SO_2 monitoring capabilities.

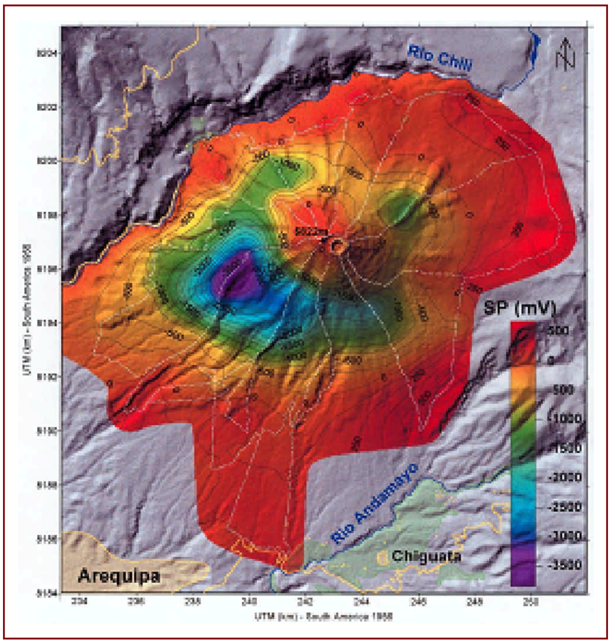
By contrast with SO_2, CO_2 is colourless and odourless, so that its presence goes unnoticed unless it is being monitored directly, for example by use of infrared sensors such as LICOR detectors. Obstacles to the routine monitoring of volcanic CO_2 from space are the relatively high CO_2 content of the atmosphere and the fact that most volcanic CO_2 emissions are not associated with eruptions, but are non-explosive, diffuse, and occur at low temperature. Because CO_2 is heavier than air, it flows along the ground, or seeps out through the soil, making it difficult to detect by satellite techniques. CO_2 plumes are deadly, however: the 1986 CO_2 emission at Lake Nyos, Cameroon, killed more than 1,700 people and much livestock. To mitigate this hazard will require ground-based monitoring and warning systems and these have yet to be developed. Similarly, volcanoes also emit HCl and HF, both of which can be hazardous, and emit other gas species as well. New instruments and techniques are available (e.g. the open-path Fourier transform infrared spectrometer, OP-FTIR) which permit the determination of all gases present in active volcanic plumes, at temperature, in the plume itself. Such tools will advance understanding of the speciation of gases in volcanic plumes and could lead to ground or even space-based monitoring of volcanic plume chemistry in order to detect the particular species that best predict volcanic activity. They should be installed at key ground monitoring stations to foster development of this technique.

As for thermal data, the observation of gases in particular and chemistry in general might profitably be extended to earthquakes. Observations of chemical composition of underground water and gas have been made for a few specific examples. Some changes in atmospheric composition (CH_4, CO_2, He, H_2) have been reported in specific cases and historical accounts mention odours associated with earthquakes. A better monitoring of such events is again required to lead to an improved understanding of the relationship between such phenomena and the processes involved in earthquakes and assess their utility as precursors.

Electromagnetic phenomena are a relatively new item for space science and represent an emerging area of research that needs to be investigated in full by the geohazards community. Russian and French satellites in 1970s and 1980s opened it up as a research topic. Related studies indicate that seismo-electromagnetic phenomena in a wide frequency range up to 100 MHz may be associated with earthquakes. Electromagnetic anomalies have been detected in the ionosphere, marked by an increase in the maximum electron density in the F layer (200-350 km) over the seismic area. Once understood in detail, such phenomena might offer promise as a precursor to be used in prediction. New missions have been announced with this aim in mind, including DEMETER - Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions - ESPERIA - Earthquake investigations by Satellite and Physics of the Environment Related to the Ionosphere and Atmosphere – KOMPAS and VULCAN. Pioneer research into the electromagnetic observations of ionosphere should be continued; other methods, such as ionospheric oxygen luminescence, should be tested.

Electromagnetic (EM) exploration techniques are in rapid development, both for methodological and technical aspects: new tomographic techniques for data inversion; new prospecting techniques; new prototypes for data acquisition. The more recent and significant applications concern the use of high resolution geoelectrical tomographies to depict the 3-D electrical conductivity structure on active faults, beneath volcanoes and landslides, the development of robust statistical techniques to investigate the inner dynamics of background noise in satellite and ground-based EM measurements particularly before anomalies suggested to be related to earthquakes and volcanoes, the investigation of the possible correlation between geochemical (CO_2, radon and other ionic concentrations) parameters, electromagnetic signals (self-potential anomalies, resistivity changes, ULF electromagnetic emissions) and surface thermal anomalies.

Gravity observations could also be used to increase our understanding of volcanic processes. Recent research using INSAR has shown that volcanoes can steadily inflate, presumably because new magma is rising within them, even though there is not yet any associated seismic activity during this steady inflation phase (Wicks and others, 2002). To be certain that inflation at a particular site is caused by magmatic intrusion (rather than pressurisation of a geothermal system), it is necessary to monitor changes in gravity at the same location. At present, relatively few volcanoes are monitored for gravity changes, so another challenge is to foster more extensive gravity monitoring, especially at deforming volcanoes where there is inflation. Absolute rather than relative gravity meters should also be used.



The image shows electrical potential field (in volt) recorded at the Misti volcano. This information can be combined with finite element modeling of the preparation phase of a volcanic eruption to propose scenario of the possible evolution of a volcano. This information could be used to issue eruption forecasts during emergency event. This work was done by CNRS-CEREGE in the framework of the activities promoted by the EMSEV (Electric, Magnetic and Electromagnetic Studies on Earthquakes and Volcanoes) that is a new Inter-Association (IAGA/IASPEI/IAVCEI) working group. (image courtesy of A. Finizola)

One of the most formidable obstacles to effective global monitoring of geohazards in general and volcanoes in particular is that activity occurs at an enormous range of time scales. Explosive eruptions may be over in a few hours to a few days, while pyroclastic flows and lahars can move at meters or tens of meters per second. Landslides may be rapid, catastrophic events on similar timescales to eruptions. For rapid events, scientists are dependent on geostationary satellites (which can take an image every 5-15 minutes), or strategically placed time-lapse or video cameras, or observers in aircraft, to capture details of the events. One scientific challenge, then, is that effective monitoring will require either a range of higher-resolution sensors on geostationary satellites, or larger constellations of low-Earth-orbiting (LEO) satellites than currently exist.

Other events are far slower: eruptions can last for decades, like the current long-lived eruptions at Montserrat (1995-present), Popocatepetl (1995-present), Etna (1991-3 and 1995-present) and Kilauea (1983-present); earthquake hazards are episodic and pose a similar need for a long-term approach, requiring continuous acquisition of data over the seismic area even through times of low activity; and subsidence can be a slow, relentless process occurring over similar timescales. These long-lived events tax the patience of scientists, emergency managers, and the general public alike. The need for continual monitoring becomes very expensive, whether it is ground-based or uses satellite observations. Improved monitoring of all kinds of long-lived geohazard events like a volcanic crisis is essential to build data archives and establish which parameters best define the geohazard's behaviour, in order to make long-term monitoring as efficient as possible. For example, one of the most fruitful areas of research in volcano seismology is the investigation of long-period quakes produced by movement of different kinds of fluids in active volcanic and geothermal systems. This area is just opening up but the computer processing capacity required to take full advantage of data from a suite of broadband seismometers (as at Kilauea) is enormous. Observatories are acquiring such data much faster than it can be processed and there is a need for large, shared international facilities.

In addition to the duration of a crisis, it is necessary to attempt to predict its initiation. Taking volcanoes as the example, about 60 of the world's 1500 potentially active volcanoes erupt in any given year. Most erupt only once a century or less frequently. Volcanoes with long repose times do not make good neighbours, however: they generally produce much larger and more dangerous eruptions when they finally awake. El Chichon (1982, repose time 600 years) and Pinatubo (1991, repose time 500 years) are recent examples of such behaviour. The population near these two volcanoes can take some comfort in the thought that it is unlikely that their volcano will erupt again in their lifetimes. However there are many such volcanoes around the world, and there is no easy way to anticipate which one will be the next Pinatubo. How is it possible to watch, both effectively and efficiently, for an event that may not occur for several centuries? Consider the example of the lahar detection network at Mt. Rainier. There the local population has supported installation of several acoustic flow detectors, to warn of a life-threatening but rare large lahar. But how often must the education process be repeated, to keep the population informed? How many times will the equipment need to be upgraded or completely replaced, if centuries pass before a lahar rumbles down from Mt. Rainier and justifies the whole enterprise? Part of establishing an effective IGOS Geohazards Theme will involve proposing how to deal rationally with these highly dangerous but relatively rare events ■

The previous chapter outlined the main elements of the strategy. This chapter proposes an action plan and implementation mechanism, describing the key players who are committed to act. The leadership roles for theme implementation and monitoring are identified. Three, five and ten-year reviews will assess implementation of short, medium and long-term actions. Feedback will be provided to the IGOS Partners and the wider geoscience community.

ACTION PLAN

A series of short, medium and long-term actions are proposed over the coming three, six and nine years, tied in to a review cycle proposed later in this chapter. They are described here in the order in which they address the strategic objectives set out in Chapter 1: building capacity; improving observations, increasing integration and promoting take-up.

None of the strategic objectives can be fully achieved without building capacity towards a coherent, integrated geohazards community. The development of a global coordinating mechanism to implement the strategy is the biggest challenge facing the geohazards IGOS. In the short term it should start with efforts to foster improved international cooperation between the key players. Building the geohazards community in this way does not necessarily require the development of a new organisation on the international stage. There are existing mechanisms within which the geohazards IGOS could work in order to achieve the same results without the overhead of establishing a formal organisation, provided that the key players are committed to make it work. Such a mechanism is proposed later in this chapter. This new home for the geohazards community would have several roles. The most important would be to lead and assess the implementation of the geohazards IGOS. But it would also be the natural body to overcome the fragmentation of the geohazards community by developing other aspects of the integration required. In the medium term it should support curriculum development within international educational programmes, international geohazards conferences and regional training workshops. These should be used to build north-south networks and so increase capacity in developing countries. In the longer term, technology transfer would follow through these networks.

For observations and key systems, the short-term priority should be to build on existing systems and initiatives. One way to do this is to seek the release of data already collected but not yet widely available. In order to get the maximum return out of these observations, the existing and planned instruments described in this report should be the subject of an early evaluation with respect to optimising sensor tasking, conversion of raw data into useful parameters and release of these products to the geohazards community. The most important examples where this should be achieved concern topographic data collected by the Shuttle Radar Topographic Mapping Mission and the ASTER satellite, which could be used to provide global topographic data at a more adequate resolution than is currently available with minimal delay. NASA and NASDA will be lobbied to achieve this. Continuity and integration of GPS, GLONAS and GALILEO geodetic observations, and especially of C-band interferometry data, will also be important. It is necessary to allow exploitation of the systematic archives already built over the past 15 years. In the medium term, the geohazards community should support the development of new instruments to provide missing observations. The primary new instrument required is an L-band SAR designed for and tasked with the observation of deformation in three dimensions based on interferometry. Research demonstrating this requirement should be disseminated as widely as possible. Lobbying should be extended to those agencies planning missions that could provide whole or partial solutions and to CEOS, in order to assess whether a dedicated mission can be achieved. In the long term, the required sensors should be launched and commissioned. On the ground, the main effort should be directed at increasing the coverage and density of seismic networks and improving real time data transmission capabilities.

Studies should be encouraged that develop an integrated approach to the geohazard issue. In the short term, an evaluation should be made of existing observations that are ready to be integrated into a useful set of standard products. Liaison should be established with, and encouragement given to, projects that seek to do this. To look at the full range of integration issues, an international project will be established on INSAR-GPS integration as a centrepiece of the geohazards IGOS. This will demonstrate the synergy to be achieved by integration in: satellite and in-situ observations; periodic and continual measurement; areal coverage and point data; Earth Observation and the geodesy; modelling and visualisation tools; and the scientists studying all three of the geohazards. In the medium term, services identified by the initial evaluation that are not yet established should be developed by using existing international funding mechanisms to initiate bids from within the geohazards community. Long-term efforts should aim at coordination of all these services globally and their integration into a geohazard observation infrastructure for the monitoring and advisory agencies akin to those already developed for Oceanography and Meteorology.

Promotion of these better ways of working requires improvements to the underlying infrastructure in order to facilitate the transfer of data, information and knowledge between different types of users in different countries. The IGOS Geohazards Theme will seek to develop operational arrangements that will make this happen more efficiently. Specifically, improvements in geohazards databases are a clear strategic goal that underpins much of the rest of this strategy. Short-term action should be three-fold. Firstly, the detailed observational requirements gathered in this study will be verified and added to the World Meteorological Organisation database. Secondly, continuity of access to reliable remote sensing data should be enhanced by taking action to make the most of existing databases, addressing issues of visibility, completeness, interoperability and pricing with the agencies who maintain them. For example, an easy improvement that could be made to several EO databases would be the provision of email-based alerts to key observatories when cloud-free data are acquired over specified targets. In a third parallel action, support should be given to the design and population of the WOVO database as an example of dedicated geohazards database that could form the design blue print for others in the future. In the medium term, efforts should be made to develop strategic datasets and document validated case histories for each of the geohazards and use these to disseminate best practice. These should be designed to accompany the database development and increase take-up by the global geohazards community by illustrating their utility. They will also facilitate the production of ancillary data for hazard mapping, guide systematic acquisitions over hazard-prone areas and drive new, targeted observations in times of crisis. In the longer term, the geohazards IGOS should seek to establish equivalent databases for earthquakes, landslides and subsidence.

Underpinning all of this will be an integrated global geohazards science research agenda, developed and coordinated by through the above mechanism and involving ICSU-IUGS, ISDR and other relevant international research organisations. In the short term, the priority should be to establish the detail of this agenda via international consultation and initiate several flagship projects on different aspects. Emerging observations linked to poorly understood processes are one such area where significant progress can be expected. In the medium term the focus should be on gases and gravity responses to magma movements in volcanoes, electromagnetic effects of volcanoes and earthquakes and triggering mechanisms for landslides, especially those related to climate change like moisture content. A tool that requires further work to be operational but could be applied to the measurement of complex deformation and motion in challenging, vegetated terrains for all the geohazards is the use of advanced forms of interferometry, including three dimensional measurements based on multiple look directions and measurements where coherence is low using active transponders. In the longer term, issues requiring data continuity can be addressed. Long time series of measurements are required to undertake an extended evaluation of potential thermal anomalies related to earthquakes. All these projects should include the participation of monitoring and advisory agencies to assess how such measurements could be integrated with the established routines that are used to monitor geohazards today.

LEADERSHIP, ASSESSMENT AND FEEDBACK

The IGOS partnership prefers to see themes led by an active partner within one of the global observing systems (GOOS for the Oceans, GTOS for Terrestrial or GCOS for Climate), to ensure integration, avoid duplication and maximise the chances of successful implementation. There is also a reluctance to erect new systems where existing ones can be used. Unlike other IGOS themes that are led by these existing global observing systems, such as the Ocean Theme whose natural home is within GOOS, the geohazards IGOS does not have an obvious main stakeholder of this kind. None of the existing global observing systems encompass the active geohazards community sufficiently. It is not clear how any of them can lead or monitor the geohazards IGOS. This poses a challenge for the implementation of the IGOS Geohazards Theme.

IGOS partners who have an interest in and actively address the geohazards issue in their programmes include several of the space agencies, including ESA, NASDA, NASA, BNSC and CNES. UNESCO and ICSU, through IUGS, represent the active ground-based element of the geohazards community within IGOS. IUGS and UNESCO run a joint international programme that has already supported development of this theme, known as the Geological Applications of Remote Sensing Programme (GARS). The projects within this programme already involve active participation of the ground-based community, including several geological surveys and the university sector. This is half of the solution. Rather than invent a new mechanism for the geohazards theme, the IGOS Geohazards Theme Team proposes to transform GARS into a suitable vehicle for theme implementation. To do this, it is necessary to add involvement from the space segment. This can be achieved by expanding GARS to include the interested space agencies, coordinated through the CEOS. The co-Chairs of the theme come from the British Geological Survey, who currently chair GARS and represent the ground-based community, UNESCO, who manage the GARS programme, and ESA, who are active within geohazards applications from an agency perspective but are not yet involved in GARS. The addition of ESA to GARS, as well as any other interested CEOS partners, will modify an existing mechanism at minimal cost to form an appropriate vehicle for implementing this theme.

Implementation will proceed via a series of international projects and capacity building activities that will need to be initiated, monitored and assessed over the next decade. GARS is well suited to this role, because this is how the programme has already operated. A series of international cooperation projects have been run by the GARS Steering Committee on various geological applications, including geohazards research with a more limited scope. The committee has representation from several developing countries and has already run projects and workshops in the developing world including Asia, Africa and the Middle East. The programme is required to report to ICSU annually and so it has some experience of assessment because it has been a necessary activity in order to support the reporting requirement. Annual assessment will be carried out by the GARS Steering Committee on a schedule designed to support reporting to both ICSU, whose requirement will continue, and the IGOS Partnership. In addition, more extensive reviews will be held at approximately three, six and nine years in order to assess progress toward achieving the short, medium and long-term actions outlined above. At these stages, the programme proposes to release a more formal assessment of progress and future prospects in the form of an update to the theme report, as well as meeting any reporting requirements thought to be necessary by the IGOS partners and ICSU.

In order to support and guide the development of the Theme it is proposed to form a high level Steering or Advisory Committee. This will have representatives from all of the key users and stakeholders groups. It is expected to include the senior management of a Space Agency, a Geological Survey, a relevant Responsible Authority and a senior member of the academic community, but it will be broadened as necessary to ensure balanced representation. It will meet annually as part of the review process, providing an independent check on progress that can also be fed to the IGOS Partners during their annual plenary, accompanying the Theme's annual report.

COMMITMENTS TO ACT

During the preparation of this Theme a strong Theme Team formed whose activities covered all of the key users and stakeholders groups. Active involvement of end users was a significant feature of an international workshop held in March 2002 and attended by ninety people from sixteen countries that was central to the Theme's definition. The key role of scientists in monitoring and advisory agencies as the link between the science and its application is recognised by their membership of the Theme Team; a large group of such organisations is intimately involved in the preparation of this proposal. Several of the longest-established geological survey organisations are active, alongside colleagues from related geoscience research institutes. The scientific user community is also well represented by active researchers in the full range of geohazards. These researchers provide a link with the International Council of Scientific Unions (ICSU). Key stakeholders such as the remote sensing industry are also well represented by space agencies, remote sensing institutes and industrial partners from the value-adding sector in several countries. The IGOS Partners are well represented in the team behind this proposal. The European Space Agency, UNESCO and ICSU have been a primary sponsor of the Theme's development. Team members come from Asia, Europe and North America.

The development of the IGOS Geohazards Theme has now been actively supported by the following organisations with staff effort and travel funds for two years:

- **Geological Surveys:** British, French, German and United States
- **Space Agencies:** European, British, Canadian and French
- **International Bodies:** UNESCO, ICSU, IUGS and GARS
- **Research Institutes:** CNR/IMAA (Italy), CNR/IRPI (Italy), CNRS/IPG-P (France), MRAC (Belgium), and RAS (Russia)
- **Private Sector:** DMT (Germany) and NPA (United Kingdom)
- **Universities:** ITC (Netherlands), Basilicata (Italy) and Bonn (Germany)

All are committed to the Theme for the remainder of 2003, during the process required before the IGOS Partnership can adopt the Theme. The milestones set out in the original proposal have been met, demonstrating the track record of the Theme Team regarding delivery. In the longer term, they all have active programmes of geohazards research and applications projects so that they have a strong incentive to remain involved. The co-chairs are committed to the delivery of this Theme beyond 2003, with the backing in place to re-shape the GARS programme and continue the IGOS Geohazards Secretariat should the Theme be adopted. There is an infrastructure in place that includes a website with the Theme documentation produced so far and an email contact mechanism, electronic file transfer facilities for the Theme Team members' work and an international contact list of interested parties ready for future dissemination and capacity building activities.

SCHEDULE

The following major milestones are envisaged:

- Publication of the Theme Report and web site update by the end of 2003.
- Establishment of the Theme Leadership through GARS by the start of 2004.
- Initiation of short-term actions during 2004, with annual reviews at the end of 2004 and 2005.
- Formal Short Term Action Assessment at end of 2006. Theme Report re-issued.
- Pursuit of medium-term actions 2007-9 with annual reviews at the end of 2007 and 2008.
- Formal Medium Term Action Assessment at end of 2009. Theme Report re-issued.
- Pursuit of long-term actions 2010-12 with annual reviews at the end of 2010 and 2011.
- Formal Long Term Action Assessment at end of 2012. Theme Report re-issued.

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AATSR Advanced Along Track Scanning Radiometer
Aftershock A ground tremor caused by the repositioning of rocks after an earthquake. It may continue to occur for as long as a few years after the initial earthquake, their intensity decreases over time
AHI Airborne Hyperspectral Imager
ALOS Advanced Land Observing Satellite
ASAR Advanced Sinthetic Aperture Radar
ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATSR Along Track Scanning Radiometer
AVIRIS Airborne Visible and Infrared Imaging Spectrometer
AVHRR Advanced Very High Resolution Radiometer
COSPEC Correlation Spectrometer
CTBT Comprehensive Nuclear-Test-Ban Treaty
DCS Data Collection System
Decade Volcano Initiative A IAVCEI contribution to **IDNDR** aimed at better utilizing science and emergency management to reduce the severity of natural disasters.
DEM Digital Elevation Model
DEMETER Detection of Electro-magnetic emissions trasmitted from earthquake regions
Earthquake A series of shock waves generated at a point (focus) within the Earth's crust or mantle.
Earthquake Magnitude A measure of the strength or energy of an earthquake as determined from seismographic information. It might be measured in the Richter scale.
Earthscope A US initiative to apply modern observational, analytical and telecommunications technologies to investigate the structure and evolution of the North American continent and the physical processes controlling earthquakes and volcanic eruptions.
EDM Electronic Distance Measurement
EMEWS European Mobile early warning system
ENVISAT ENVironmental SATellite
EO Earth Observation
ESPERIA Earthquake investigation by satellite and physic of the Environment Releted to the Ionosphere and Atmosphere
FTIR Fourier Transform Infrared spectrometer
GEOWARN Geo-spatial warning system
GIS Geographic Information System
GOES Geostationary Operational Environmental Satellite
GPS Global Positioning System
Ground instability Term encompassing all sizes and shapes of different failures. Mobilized material include earth or soil, debris, rock, and reef. Whereas different classifications are available in the scientific literature, with respect to the main physical mechanism, which determines ground instability, the following categories may be considered: a) Gravitational Force; b) Forces caused by Phase Changes; c) Tectonic Forces
Ground subsidence Term used for a wide variety of a sudden or gradual downward-upward with no or very little horizontal ground movements of earth. This motion might be caused by ground water withdrawal, underground storage, collapse of buried natural or man-made cavities and settlement of loose sediments. It could be considered as a gravitational motion if the phenomena related to the fluid (liquid and gas) extraction were excluded. They represent a major challenge more specifically in industrial countries due to either the exploitation of the underground resources (e.g. mines) or construction of underground facilities (e.g. subways, sewage system, tunnels) during the past two centuries.
HyMAP Hyperspectral Mapping
ILP International Lithosphere Program
InSAR SAR Interferometry
IPR Intellectual Property Rights
IR Infra Red
JERS Japanese Earth Resources Satellite
Lahar Debris flow or mudflow consisting largely of volcanic material. Lahars can be triggered during an eruption by interaction of erupting lava with snow, ice, lakes, streams or heavy rainfall, as occurred during the 1985 eruption of Nevado del Ruiz. Secondary lahars, which have occurred at Pinatubo for a decade following the 1991 eruption, can have as much impact on the surrounding area as the eruption itself. Lahars travel downstream for distances of 20-300 km, at average speeds of 10-30 km/hour. (Data from Blong, 1984).
Landslide A downward movement of masses of soil or rock material
Lava Magma extruded by a volcano
LEO Low-Earth-Orbiting
LiDAR Light Detection and Ranging
MERIS Medium Resolution Imaging Spectrometer
MIR Mid InfraRed
MISR Multi-Angle Imaging Spectro Radiometer
MIVIS Multispectral Infrared and Visible Imaging Spectrometer
MODIS Moderate-Resolution Imaging Spectroradiometer
OP-FTIR Open-Path Fourier Transform Spectrometer
PALSAR Phase Array type L-band Synthetic Aperture Radar
PGA Peak Horizontal Ground Acceleration
Plate tectonics study of the major architectural features of the Earth's crust
Pyroclastic flow Avalanches of hot ash and lava fragments, volcanic gas and air, formed during explosive eruptions or by collapse of growing lava domes. Their internal temperatures are 200-1100EC and they move at speeds of 10-100 m/sec. (Data from Blong, 1984).
RADARSAT RADAR SATellite
Regolith Unconsolidated rock material resting on bedrock

SAR Synthetic Aperture Radar
Seismic Wave One of a series of progressive disturbances that reverberate through the Earth to transmit the energy released from an earthquake. According to their characteristics they are subdivided in: L, S and P waves
SEVIRI Spinning Enhanced Visible and InfraRed Imager
SRTM Shuttle Radar Topography Mission
Tephra explosion ejection of fragmental volcanic products through the vent. Size of the products range from fine dust to massive blocks
TIR Thermal InfraRed
TOMS Total Ozone Mapping Spectrometer
Tsunami A gravity wave that follows a short-duration, large-scale disturbance of the free sea surface
VALVE Volcano analysis and visualization environment
Volcano A vent or fissure in the Earth's crust through which molten magma, hot gases and other fluids escape to the surface.

AVI	Aree Vulnerate Italiane
BGS	British Geological Survey
BNSC	British National Space Centre
BRGM	Bureau de Recherches Geologiques et Minieres
CCRS	Canadian Centre for Remote Sensing
CEOS	Committee on Earth Observation Satellites
CEREGE	Centre Europ en de Recherche et d'Enseignement des G osciences
CNES	Centre National d'Etudes Spatiales
CNR	Consiglio Nazionale delle Ricerche
CNRS	Centre National de la Recherche Scientifique
CNSS	Council of the National Seismic System
CSAV	Centre for the Study of Active Volcanoes
DMSG	Disaster Management Support Group
DMT	Deutsche Montan Technologie
DUE	Data Users Element
EC	European Commission
EMSEV	Electric, Magnetic and Electromagnetic Studies on Earthquakes and Volcanoes
ESA	European Space Agency
GARS	Geological Applications of Remote Sensing
GCOS	Global Climate Observing System
GMES	Global Monitoring for Environment and Security
GOOS	Global Ocean Observing System
GSE	Gmes Service Element
GTOS	Global Terrestrial Observing System
IAGA	International Association of Geomagnetism and Aeronomy
IASPEI	International Association of Seismology and Physics of the Earth's Interior
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
ICSU	International Council of Scientific Unions
IDNDR	International Decade for Natural Disaster Reduction
IGOS	Integrated Global Observing Strategy
IMAA	Institute of Methodologies for Environmental Analysis
IPG-P	Institut de Physique du Globe de Paris
IRIS	Incorporated Research Institutions for Seismology
ITC	International Institute for Geo-Information Science and Earth Observation
UGS	International Union of Geological Sciences
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NGDC	National Geophysical Data Center
NGO	Non Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
NPA	Nigel Press Associates
PHIVOLCS	Philippine Institute of Volcanology and Seismology
RAS	Russian Academy of Sciences
RMCA	Royal Museum for Central Africa
UN	United Nations
UNAVCO	University NAVSTAR Consortium
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNIBAS	University of Basailicata
USGS	United States Geological Survey
VDAP	Volcano Disaster Assistance Program
VOMIR	VOlcano Monitoring by InfraRed
WMO	World Meteorological Organization
WOVO	World Organisation of Volcano Observatories
WSSD	World Summit on Sustainable Development

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IGOS GEOHAZARDS

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